HUNTING FOR SUSY AT ATLAS

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Outline

Introduction

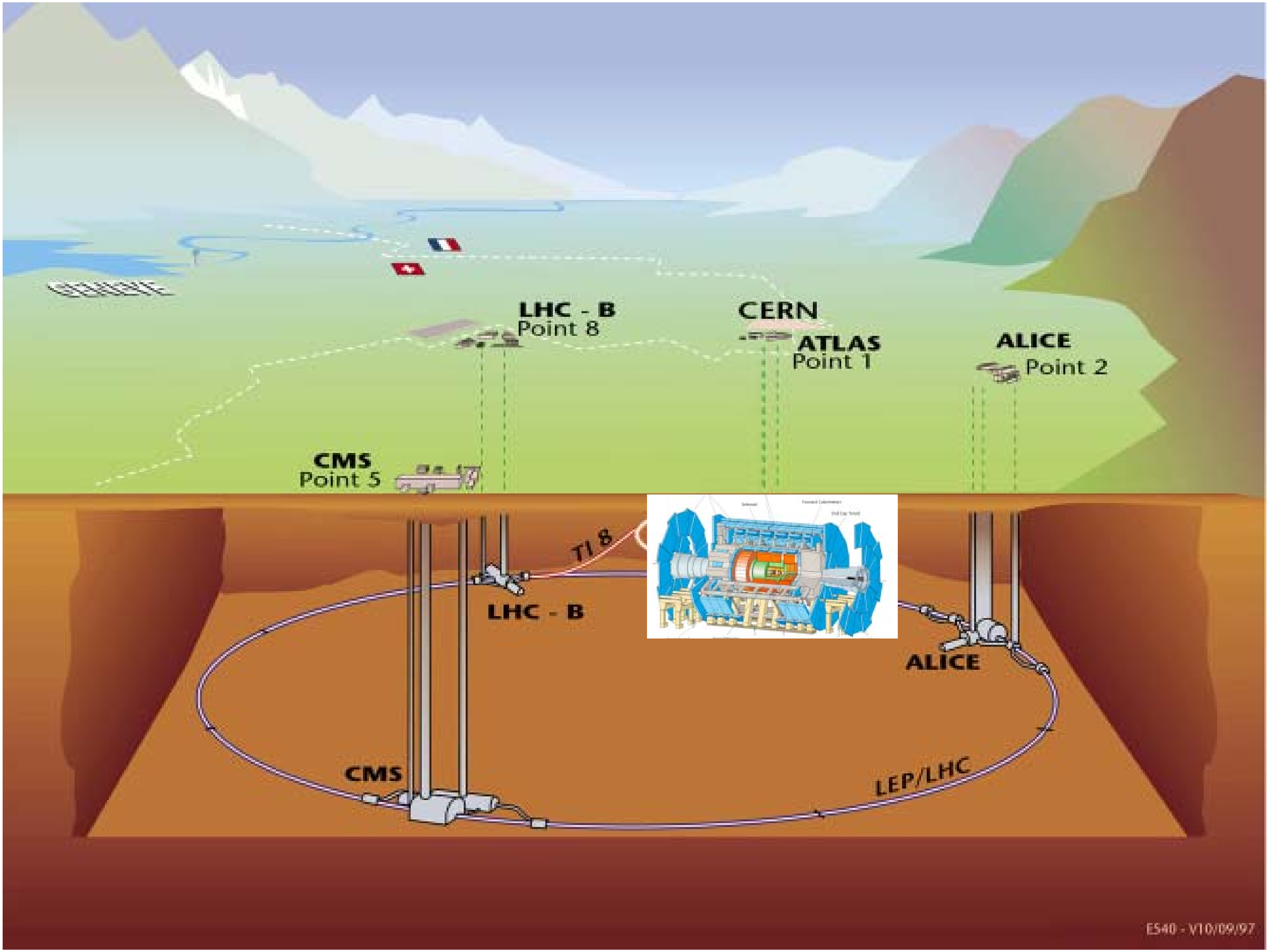
- The LHC
- The ATLAS experiment

Supersymmetry

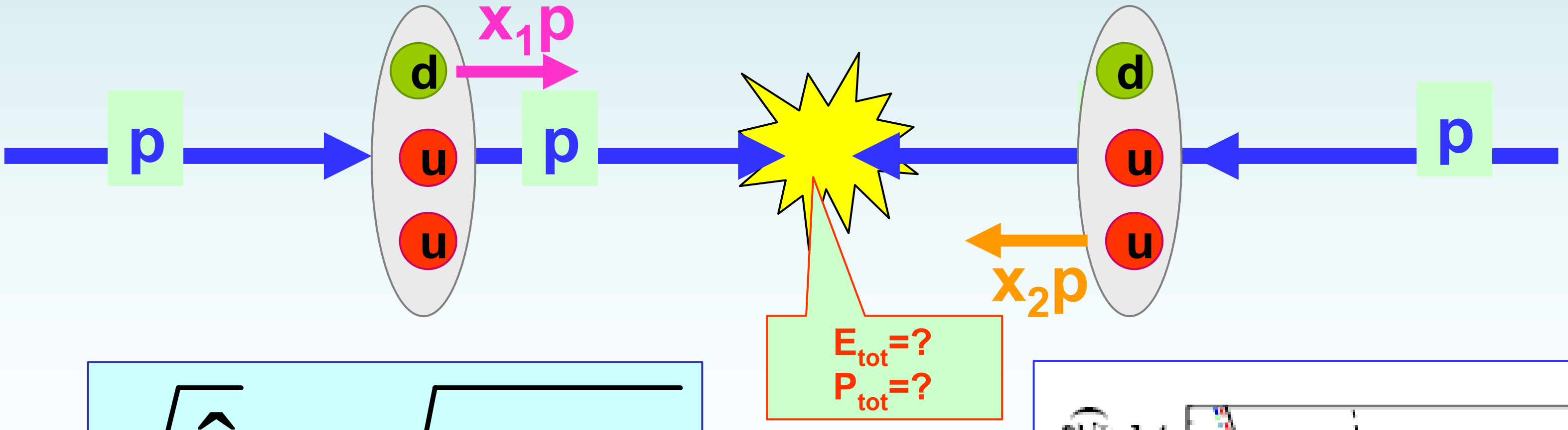
- Motivations
- Benchmarks and strategy
- Early physics reach

Conclusions

THE LHC AND ATLAS


LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
TI 8
Solenoid
Forward Calorimeters
End Cap Toroid
LHC - B
ALICE
CMS
LEP/LHC
E540 - V10/09/97

Collisions at a hadron collider



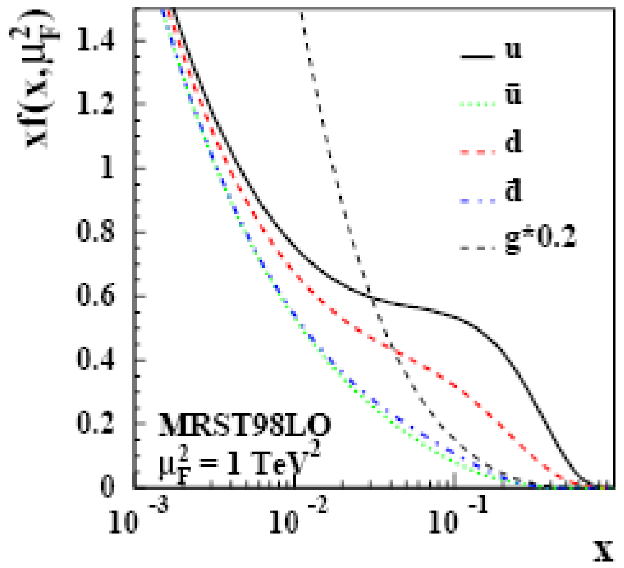
E_{tot}=?
P_{tot}=?

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$$

No constraints on total initial energy

Broad range of √s → good for discovery!

All possible processes are “on” simultaneously



PDFs

LHC's Main Goals

Elucidate mechanism for EW symmetry breaking

Search or Higgs boson in O(100 GeV)-O(1 TeV) range

If no light Higgs is found, study WW scattering at high mass

Look for evidence of new physics at TeV-scale

Deviations from Standard Model predictions in data

Supersymmetry

(and Exotics…)

LHC’s Main Goals

Elucidate mechanism for EW symmetry breaking

Search or Higgs boson in O(100 GeV)-O(1 TeV) range

Not Today !

If no light Higgs is found, study WW scattering at high mass

Look for evidence of new physics at TeV-scale

Deviations from Standard Model predictions in data

Supersymmetry

(and Exotics…)

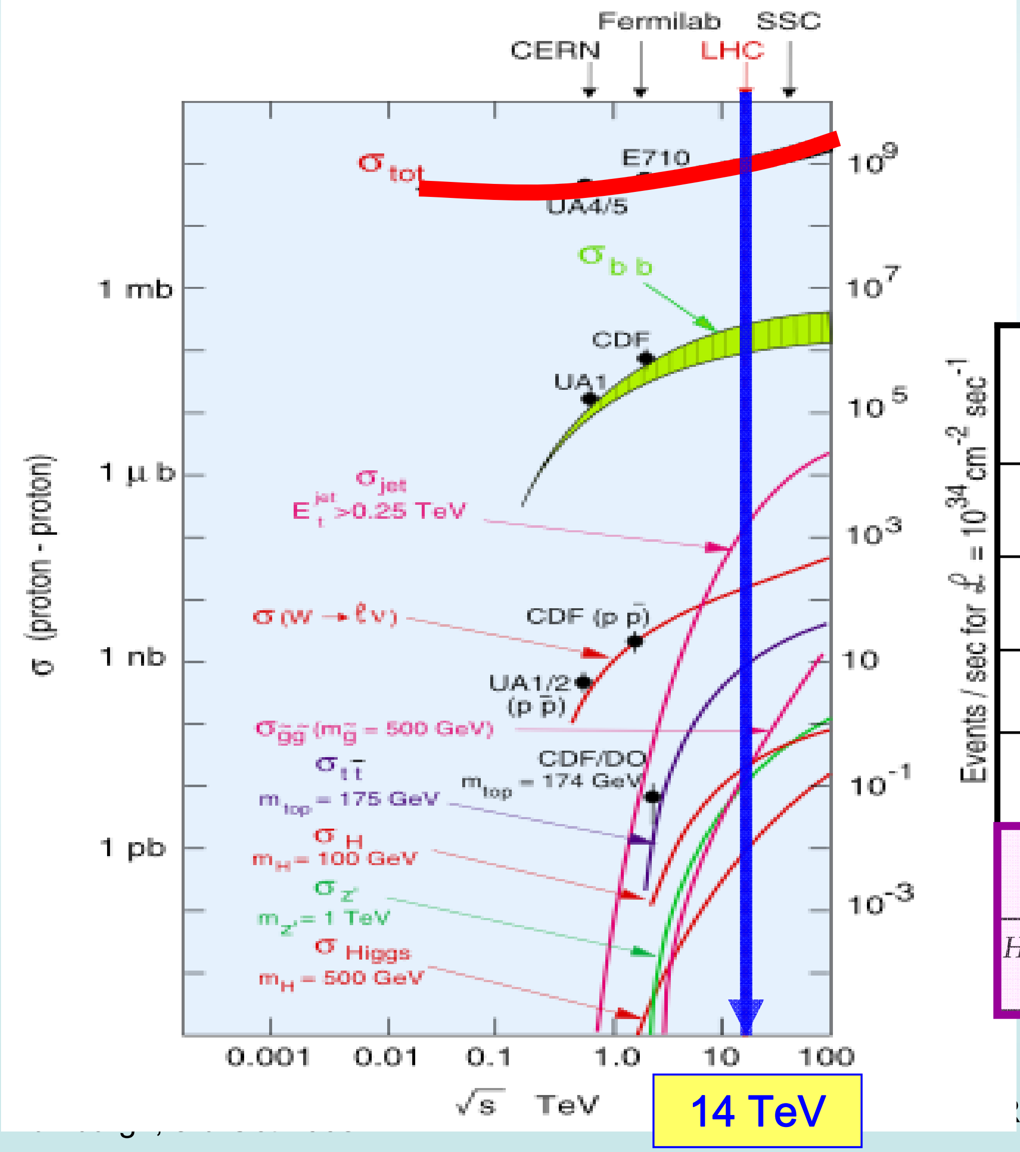
Design luminosity:

"Low" = (2x)10^{33} cm^{-2} s^{-1} (O(10 fb^{-1}) / yr)

"High" = 10^{34} cm^{-2} s^{-1} (O(100 fb^{-1}) / yr)

$$\sigma_{pp}^{tot} \sim 110 \text{ mb} \quad (\sigma_{pp}^{inel} \sim 70 \text{ mb})$$

"Minimum Bias" rate: O(10^9 Hz) !!



Process	σ (nb)	#evts [10 fb^{-1}]	Rates(Hz) ["high" L]
$b\bar{b}$	500 μb	5x10^{12}	5x10^6
$W \to e\nu$	15 nb	~10^8	150
$Z \to ee$	1.5 nb	~10^7	15
$t\bar{t}$	800 pb	~10^7	10
$\tilde{g}\tilde{g}$ (1 TeV)	~1 pb	~10^4	10^{-2}
$H(200 \text{ GeV}) \to 4\ell$	~10 fb	~10^2	10^{-4}

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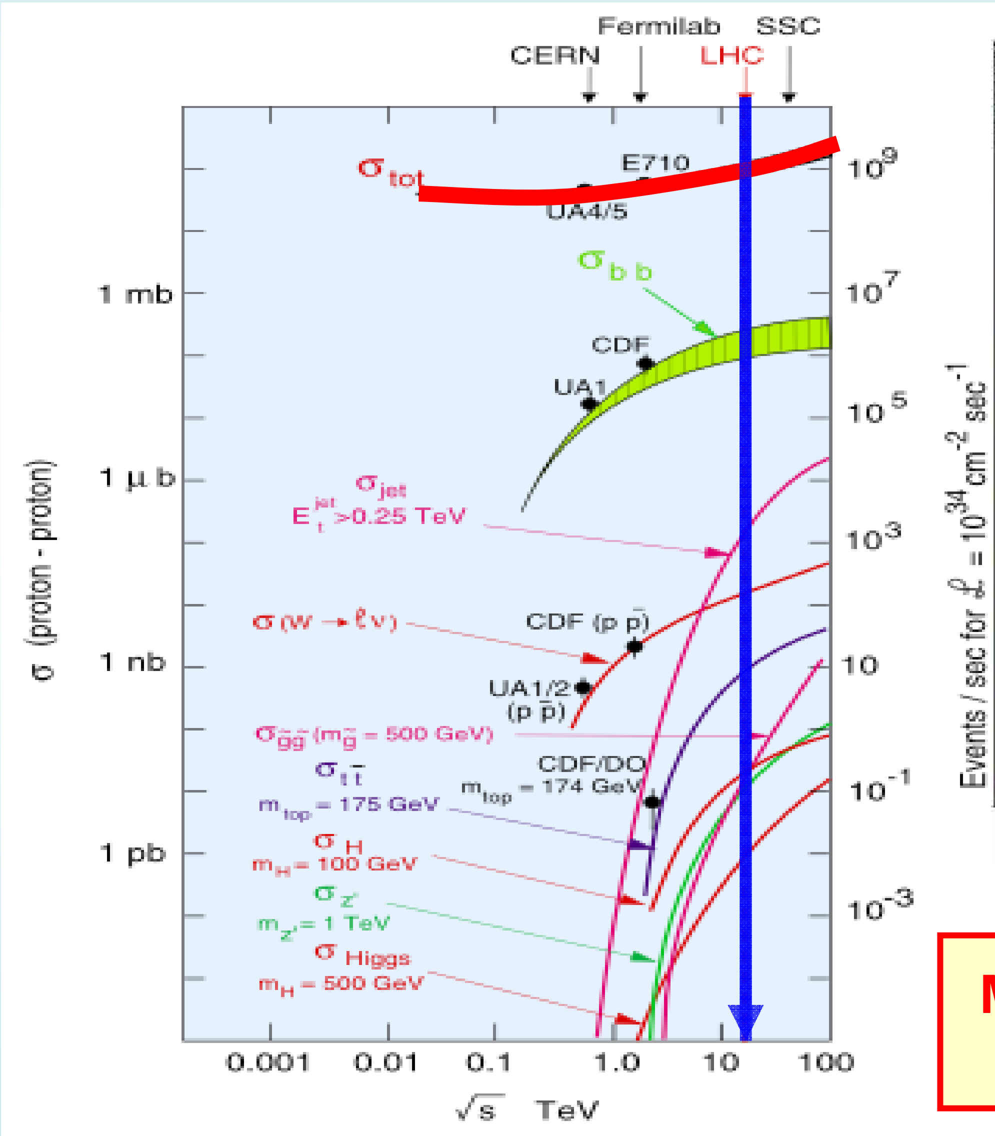
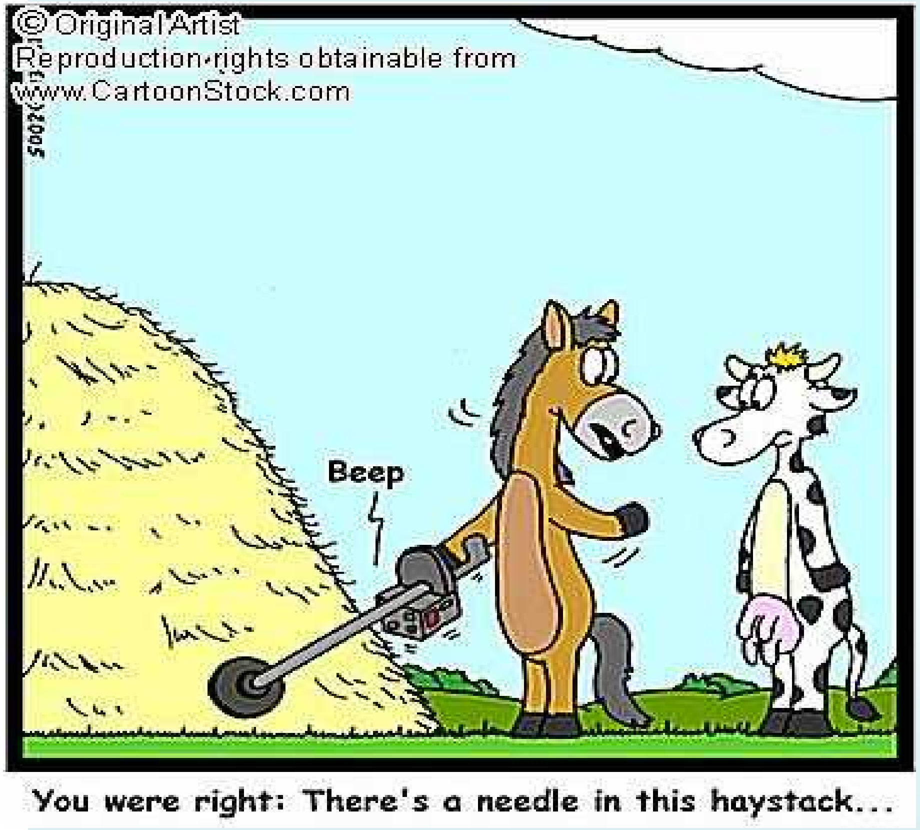




You were right: There's a needle in this haystack...

Must rely on distinctive signatures

leptons, photons, b-jets, missing E$_T$, …

Detector Requirements

Excellent position and momentum resolution in central tracker

- b-jets, taus

Excellent ECAL performance

- electrons, photons
- v. good granularity (energy and position measurements)

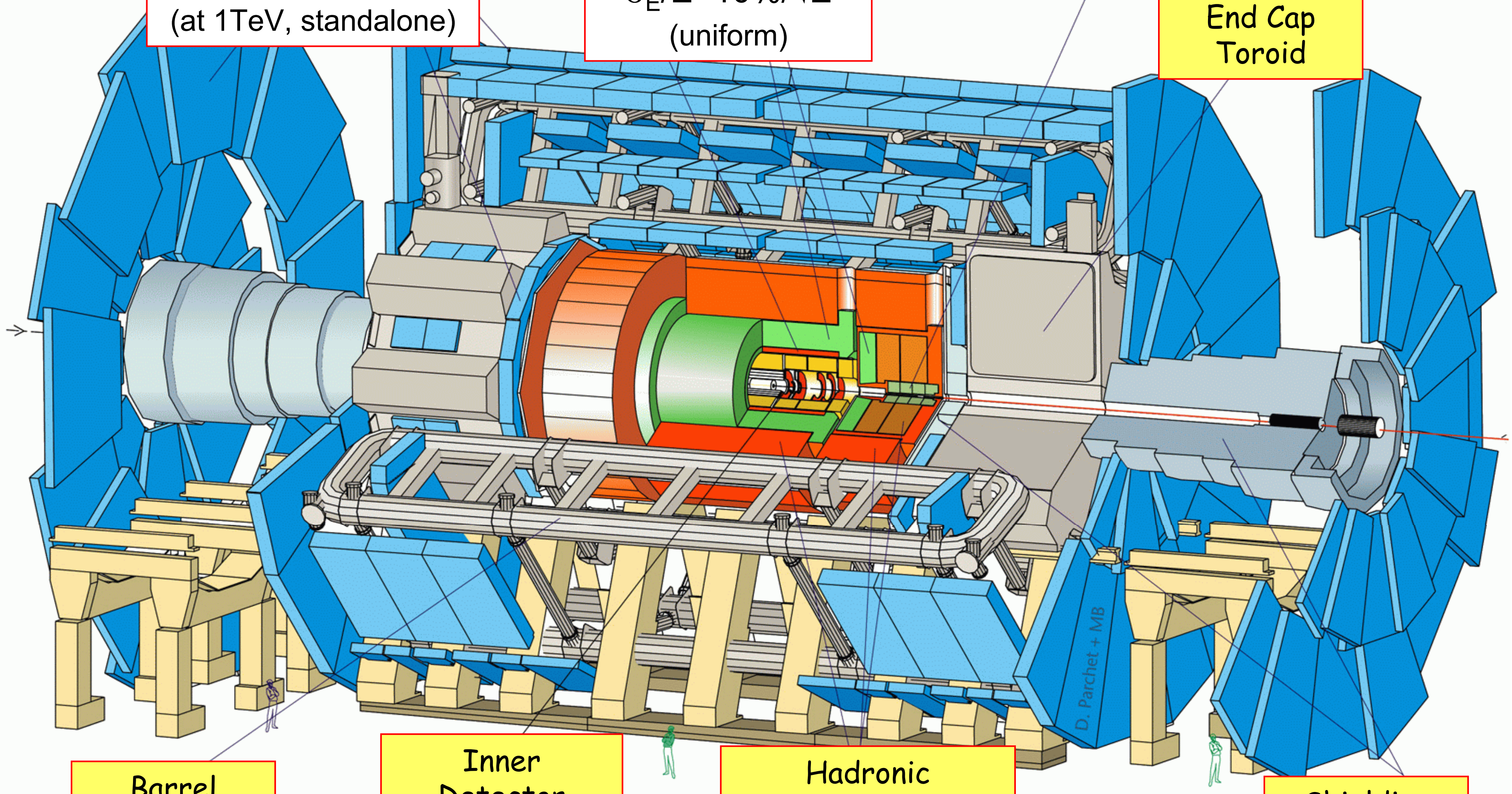
Good HCAL performance

- jets, Etmiss (neutrinos, SUSY stable LSP, etc)
- good granularity (energy and position measurements)
- good η coverage (hermeticity for Etmiss measurements)

Excellent muon identification and momentum resolution

- from “combined” muons in external spectrometer + central tracker

The ATLAS Detector



Muon Detectors

$\sigma(p_T)/p_T \sim 7\%$

(at 1TeV, standalone)

Electromagnetic Calorimeters

$\sigma_E/E \sim 10\%/\sqrt{E}$

(uniform)

Forward Calorimeters

End Cap Toroid

Barrel Toroid

Inner Detector

$\sigma(p_T)/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$

Hadronic Calorimeters

$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$

Shielding

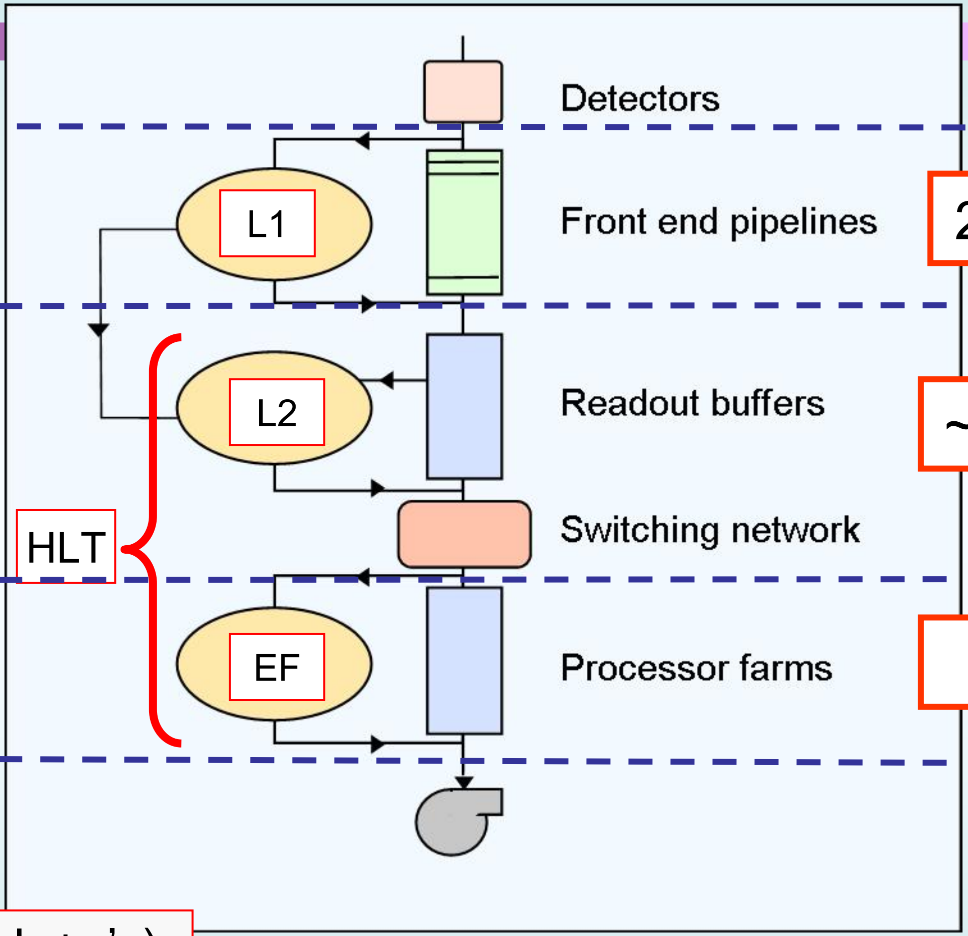
The ATLAS Trigger

40 MHz input rate
(bunch crossing)

O(100 kHz) L1 rate

O(1 kHz) L2 rate

O(100 Hz) output rate
(on tape)



2.5 μs

~10 ms

~1 s

L1: Hardware based (calo+μ's)

HLT: Software based

Three levels
(L2 + EF = HLT)

Event size
1-2 MBytes

(HLT = High-Level Trigger)

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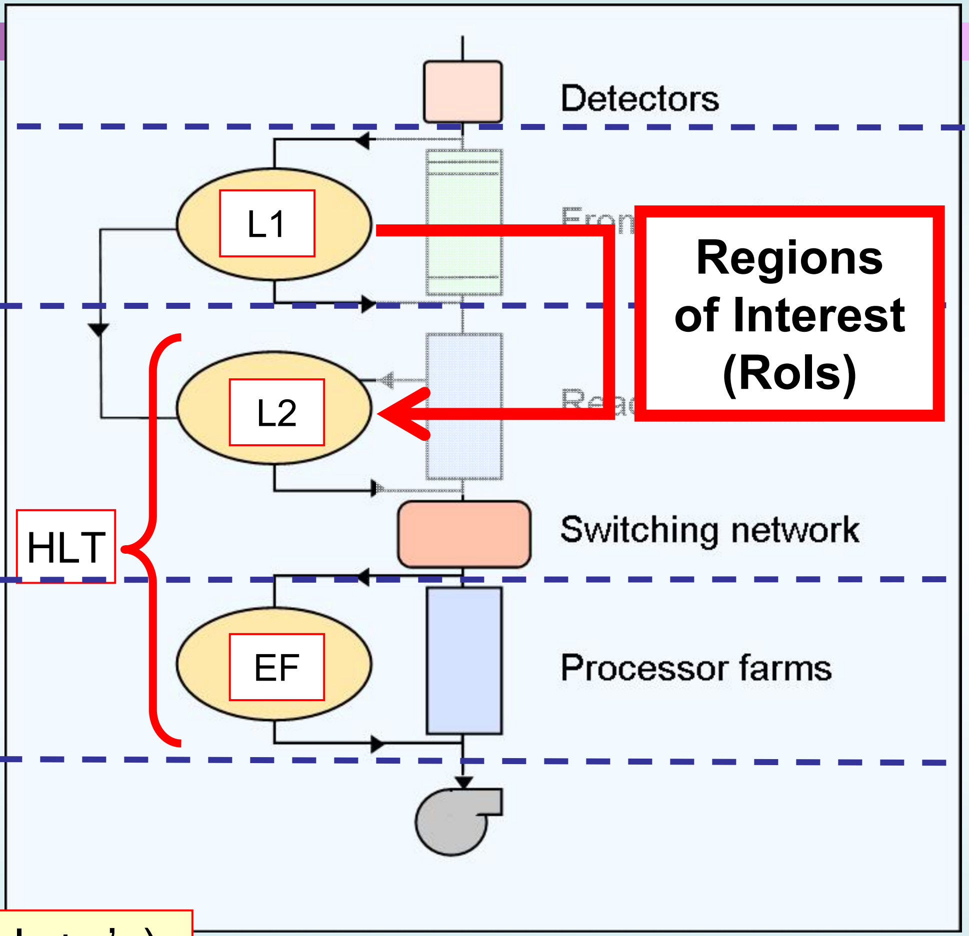

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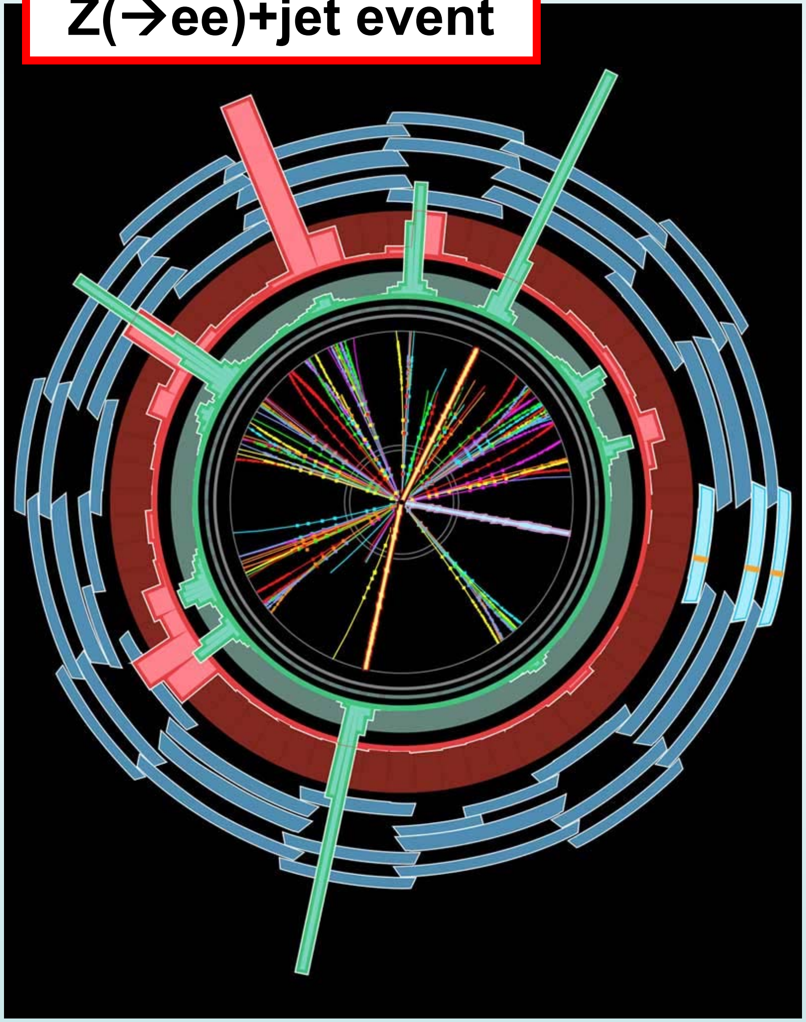
The ATLAS High-Level Trigger

Z(→ee)+jet event



“Seeded” and “stepwise”

- early rejection of uninteresting events
- minimum amount of processing
- maximum flexibility

RoIs “seed” trigger reconstruction chain

- <10% of the event accessible at L2
- EF seeded by L2 (“offline” reco)

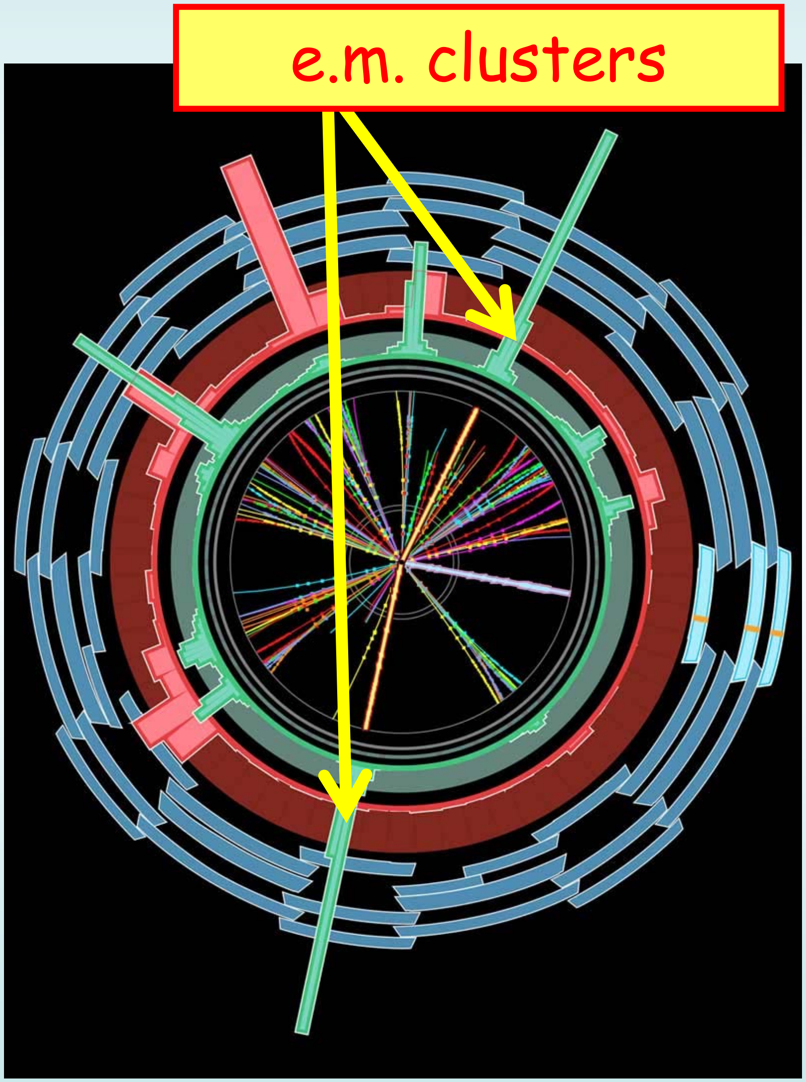
Reduced CPU/ bandwidth requirements

- but increased complexity

Avoid biases but retain flexibility

- to account for the “unexpected”

The ATLAS High-Level Trigger



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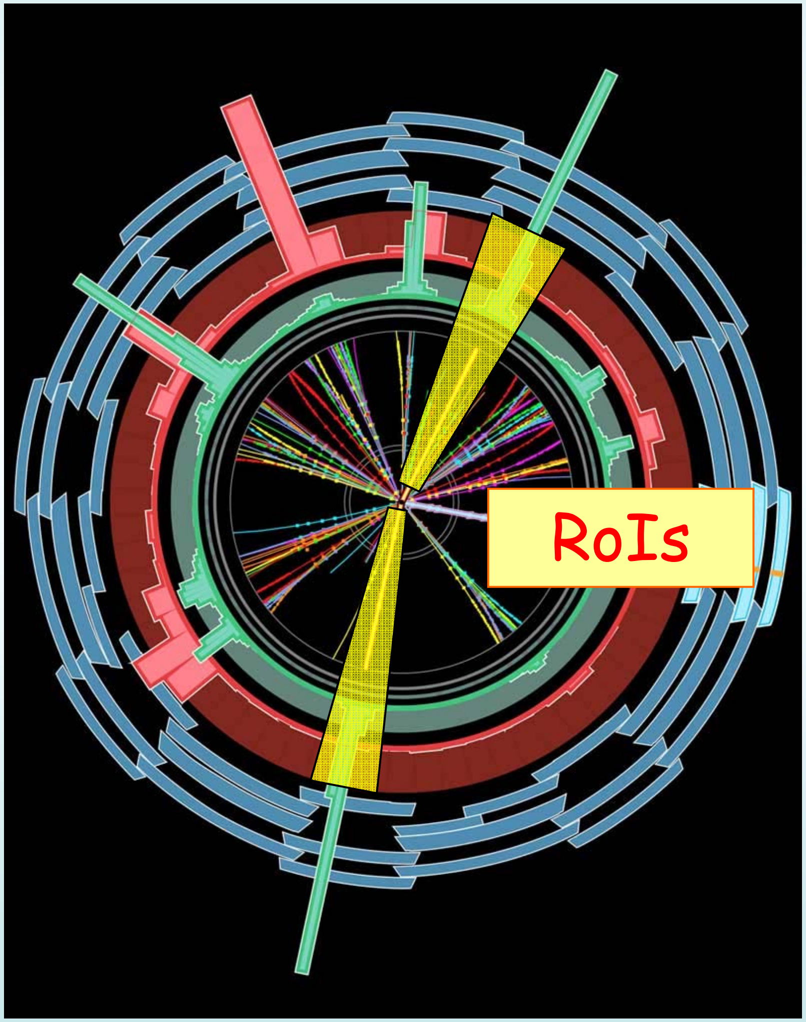

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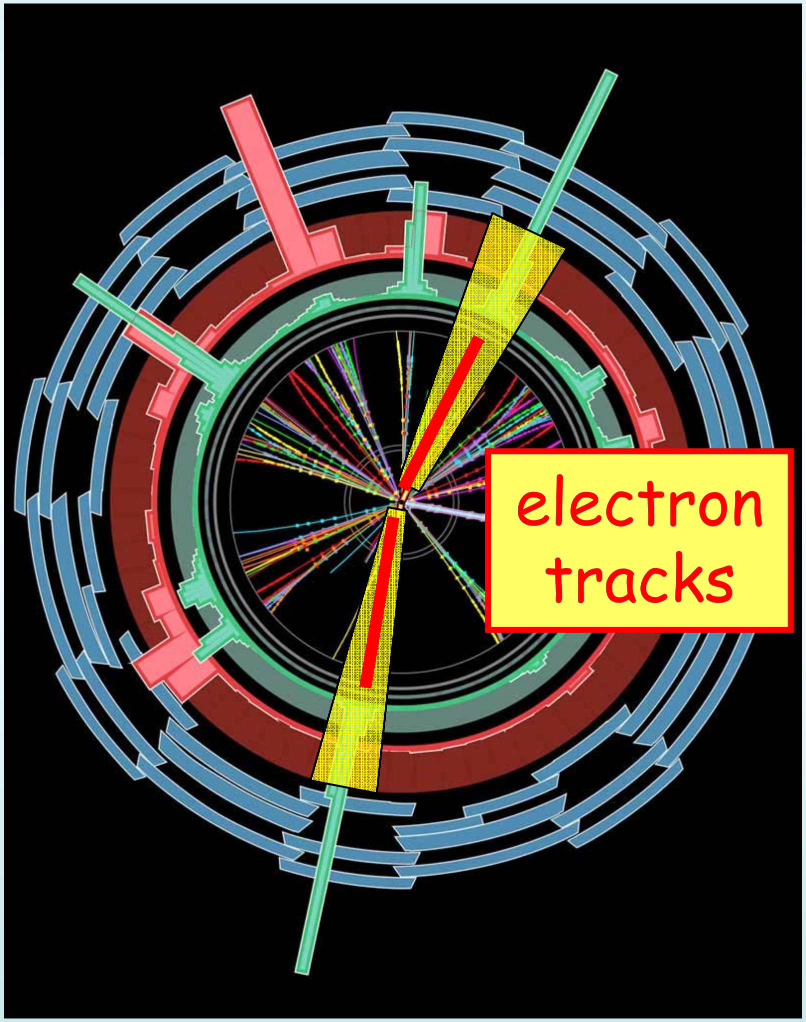

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Early Physics Triggers for SUSY

Early SUSY searches will mainly concentrate on inclusive signatures

- multi-jets
- large missing transverse energy
- possibly leptons

(see later)

Crucial to keep the trigger selection criteria as simple as possible

- to minimize biases and systematic effects

Experience shows that an Etmiss trigger takes time to become established

- due to instrumental effects
- Etmiss also crucial to define control/signal regions

Strategy is to de-emphasize Etmiss trigger in early days

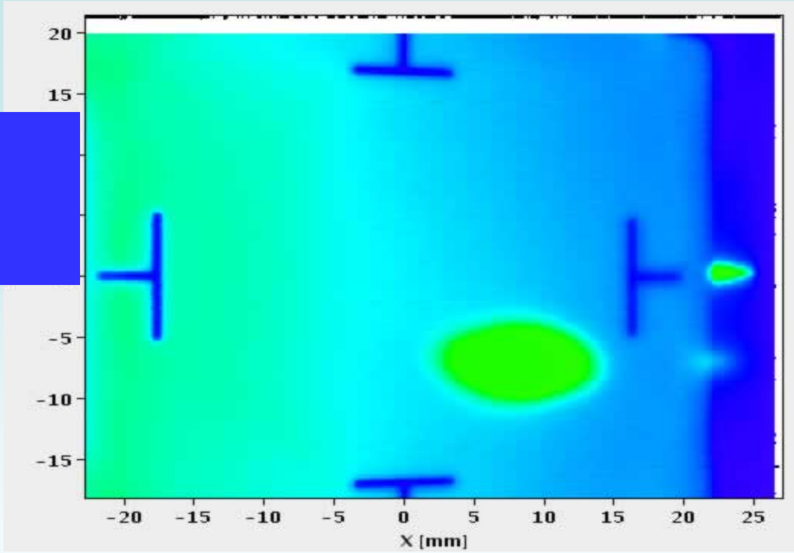
- rely on leptons and/or jets instead

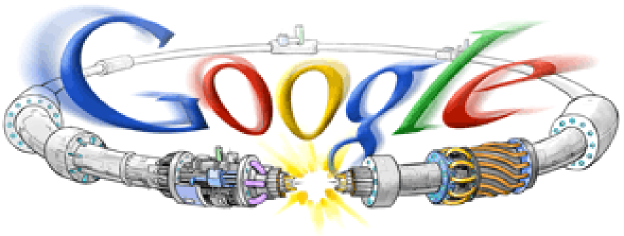
STATUS

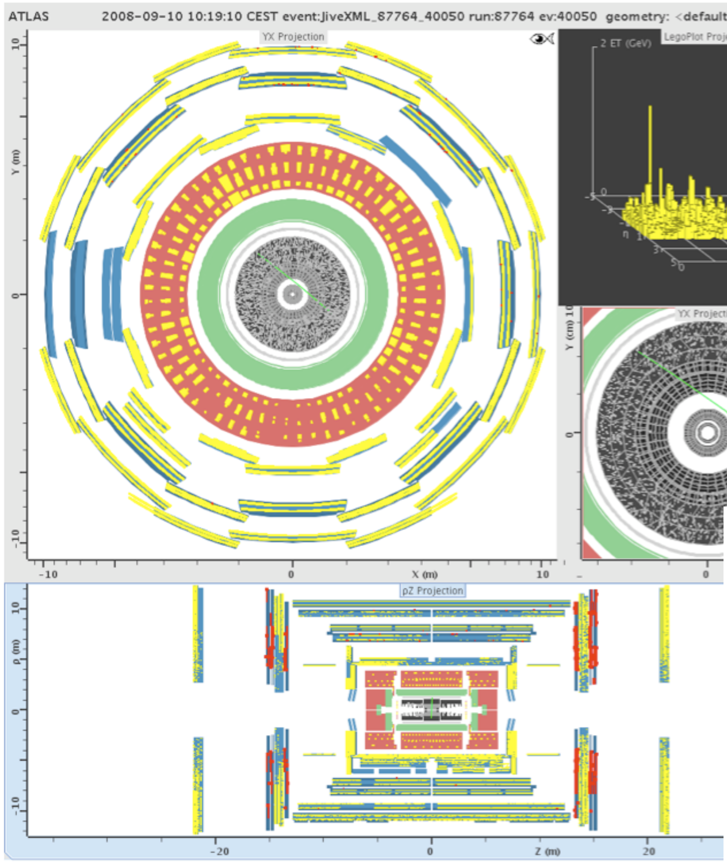
The world did not come to an end…

September 10, 2008

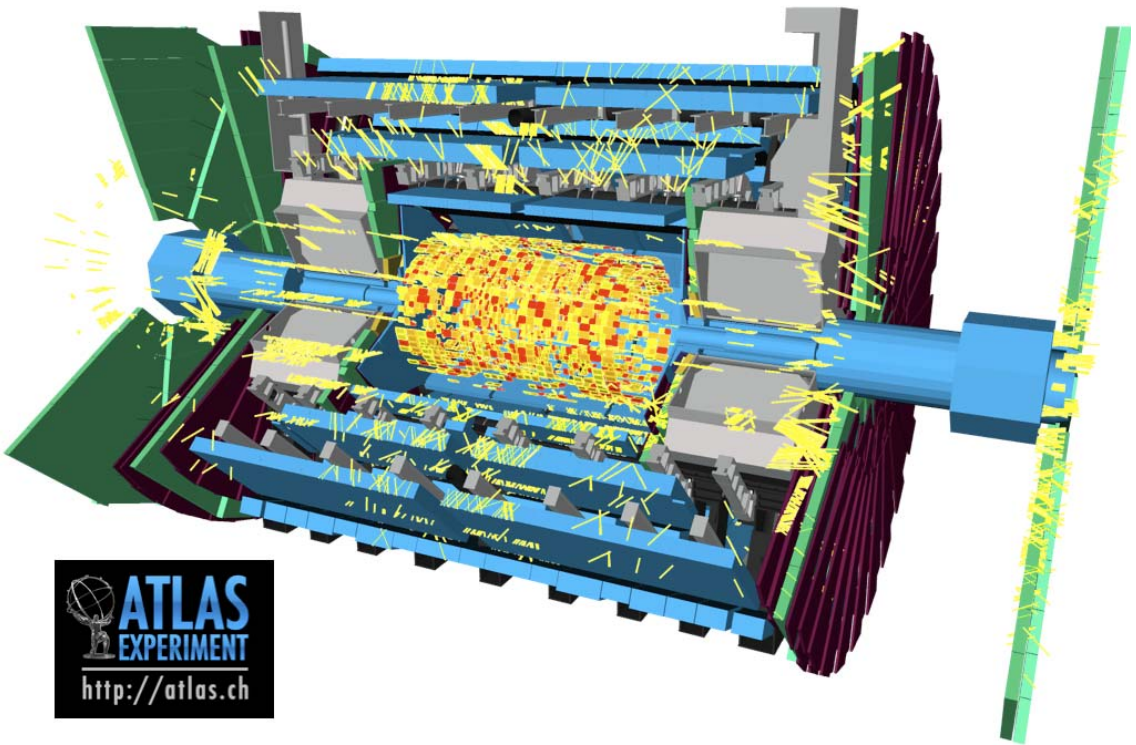
A Great Start…



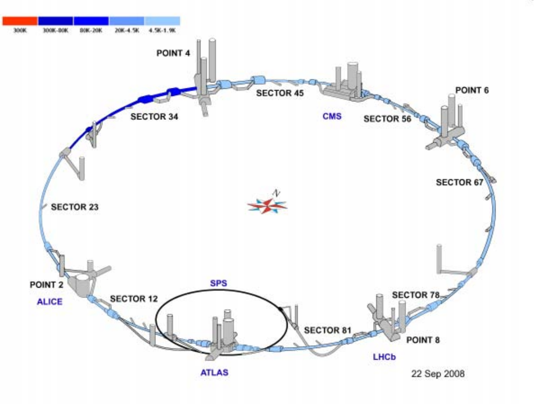




First beam event in ATLAS



Unfortunately…



Incident in LHC sector 34

Geneva, 20 September 2008.

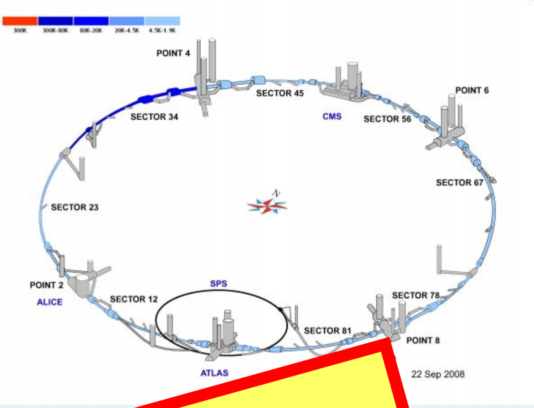
During commissioning (without beam) of the final LHC sector (sector 34) at high current for operation at 5 TeV, an incident occurred at mid-day on Friday 19 September resulting in a large helium leak into the tunnel. Preliminary investigations indicate that the most likely cause of the problem was a faulty electrical connection between two magnets, which probably melted at high current leading to mechanical failure. CERN ’s strict safety regulations ensured that at no time was there any risk to people.

A full investigation is underway, but it is already clear that the sector will have to be warmed up for repairs to take place. This implies a minimum of two months down time for LHC operation. For the same fault, not uncommon in a normally conducting machine, the repair time would be a matter of days.

Further details will be made available as soon as they are known.

(R.Aymar, CERN DG)

Unfortunately…



22 Sep 2008

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First collisions expected in 2009

(R.Aymar, CERN DG)

SUPERSYMMETRY

Why go Beyond the Standard Model?

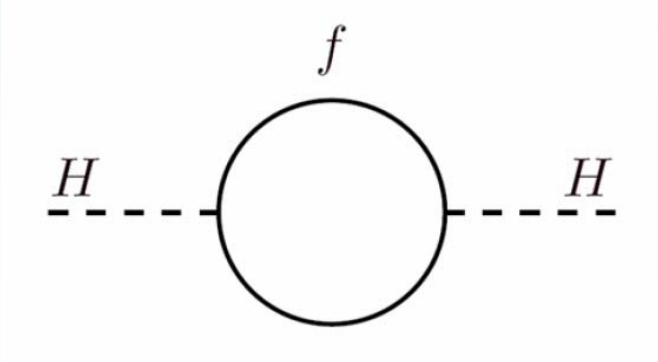
Despite its many successes, the Standard Model is widely believed to be only an effective theory, valid up to a scale $\Lambda << M_{Planck}$

- Gravity not included in SM
- Hierarchy/naturalness problem:
  - $M_{EW} << M_{Planck}$
  - Fine-tuning
- Unification of couplings

Need a more fundamental theory of which the SM is only a low-energy approximation

Hierarchy Problem and Naturalness

In SM, loop corrections to Higgs boson mass:



$$\delta m_H^2 = O\left(\frac{\alpha}{\pi}\right)\boxed{\Lambda^2} \rightarrow$$

Theory cut-off

Natural scale of scalar mass is very large!

These corrections, which are large, give rise to fundamental problems when requiring that:

m_H << fundamental mass scale (i.e. M_{Planck})

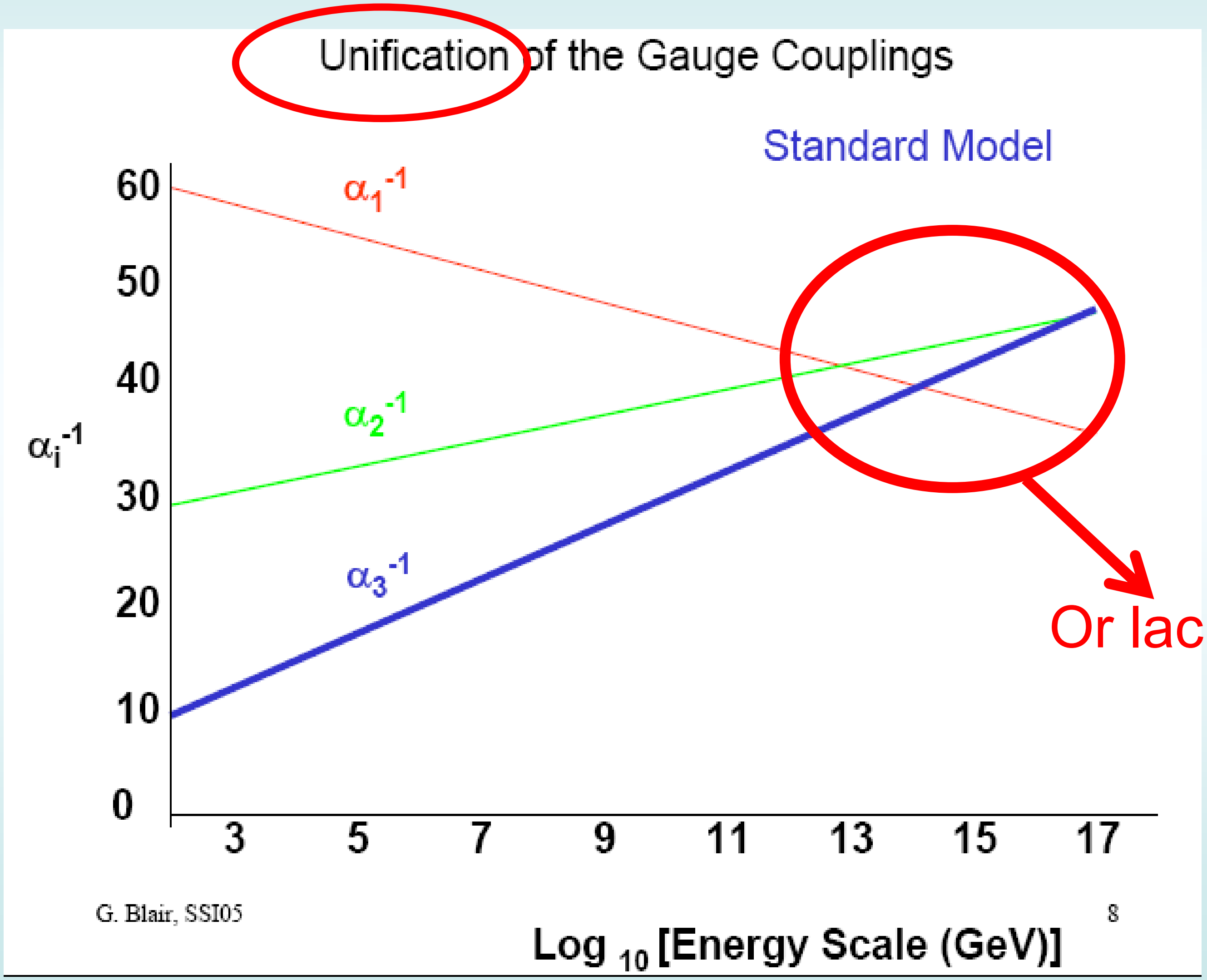
(hierarchy problem)

Corrections δm_H^2 to Higgs mass should not be >> m_H^2

(naturalness)

Need either fine-tuning or protective symmetry!

Unification of Coupling Constants in the SM



Or lack of it…

Supersymmetry

Space-time symmetry that relates fermions (matter) and bosons (interactions)

$$\boxed{Q|boson\rangle = |fermion\rangle \quad \text{and} \quad Q|boson\rangle = |fermion\rangle}$$

Further doubling of the particle spectrum

- Every SM field has a "superpartner" with the same mass
- Spin differs by 1/2 between SUSY and SM partners
- Identical gauge numbers
- Identical couplings

Superpartners have not been observed

- SUSY must be a broken symmetry

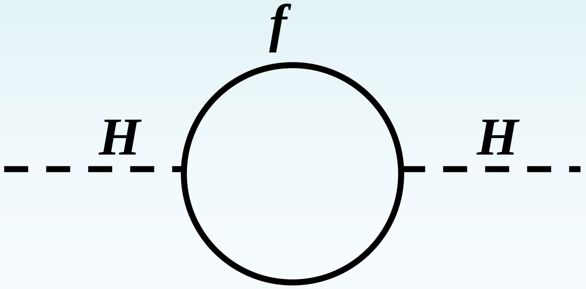
But SUSY-breaking terms in Lagrangian must not re-introduce quadratic divergences in theory !

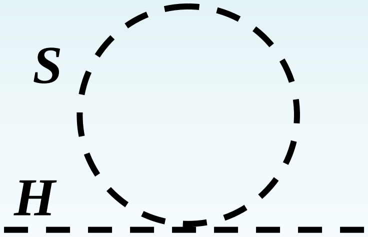
Minimal Supersymmetric Standard Model

Standard Model Particles and Fields		**Supersymmetric Partners**			
		Interaction Eigenstates		**Mass Eigenstates**	
Symbol	**Name**	**Symbol**	**Name**	**Symbol**	**Name**
$q = u, d, c, s, t, b$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_R, \tilde{l}_L$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$l = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^{\pm}$	W-boson	$\tilde{W}^{\pm}$	wino	$\tilde{\chi}^{\pm}_{1,2}$	chargino
H_u^+, H_d^-	charged Higgs boson	$\tilde{H}_u^+, \tilde{H}_d^-$	charged higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^0	W⁰-field	$\tilde{W}^0$	wino		
H_u^0, H_d^0	neutral Higgs boson	$\tilde{H}_u^0, \tilde{H}_d^0$	neutral higgsino		

Supersymmetric Solution to Divergences

Bosonic and fermionic diagrams now give **equal and opposite** contributions:





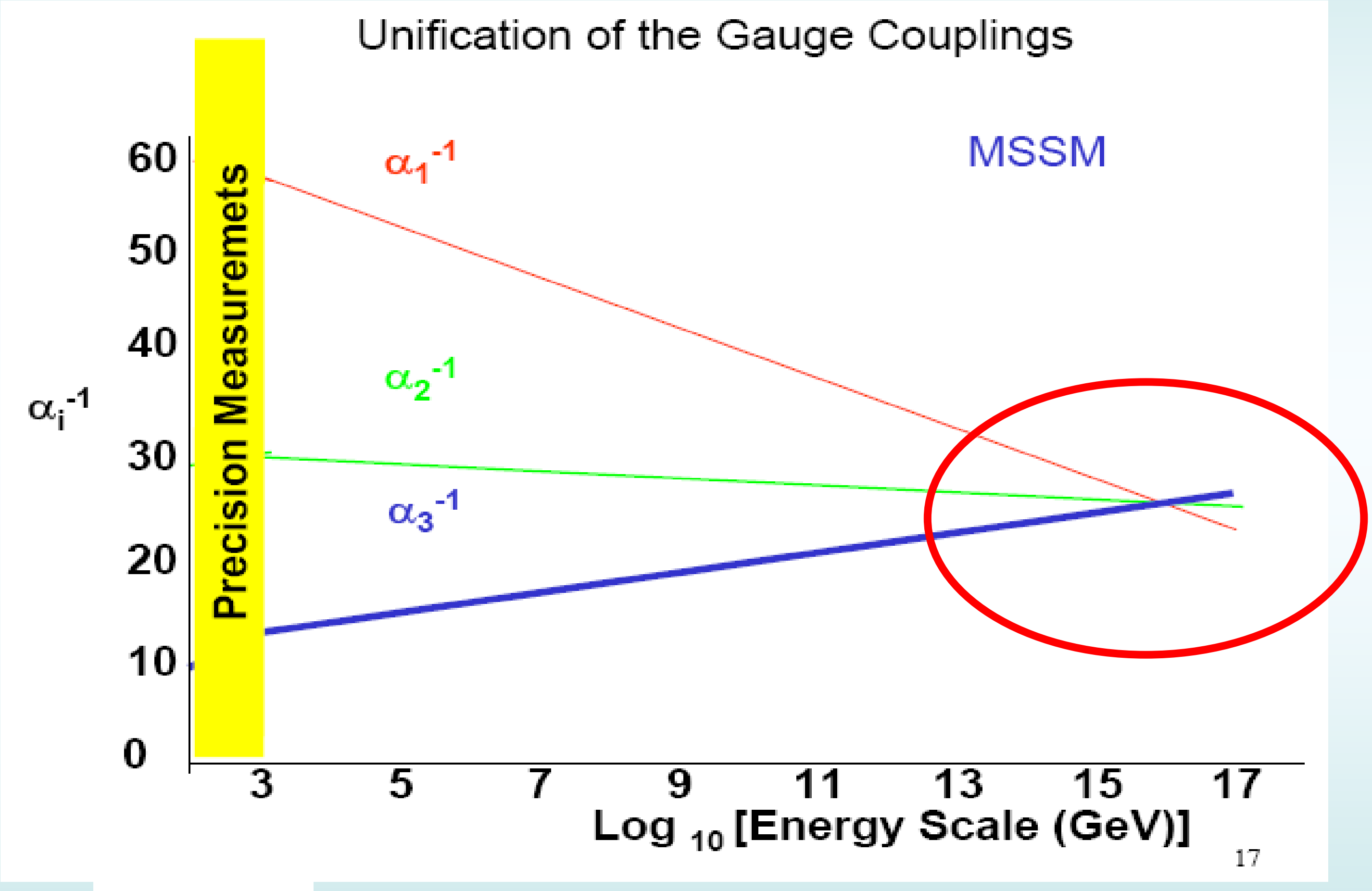
$$\delta m_H^2 = \left(\frac{g_f^2}{16\pi^2}\right)\left(\Lambda^2 + m_f^2\right) - \left(\frac{g_S^2}{16\pi^2}\right)\left(\Lambda^2 + m_S^2\right) = O\left(\frac{\alpha}{4\pi}\right)\left| m_S^2 - m_f^2 \right|$$

If #boson = #fermions and they have equal masses and couplings, the quadratic divergences cancel

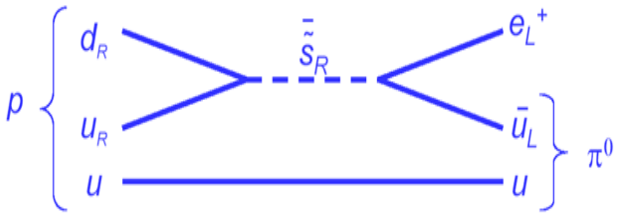
Higgs mass correction $\delta m_H^2 < m_H^2$ if $\left| m_S^2 - m_f^2 \right| <\sim \mathrm{TeV}^2$

Gauge boson contribution cancelled by gaugino contribution

Unification of Coupling Constants in MSSM



Now unification of strong, weak and e.m. forces achieved at ~M_{GUT}



R-parity

A new symmetry is introduced to cure unwanted effects (e.g. proton decay) from lepton and baryon number violating terms in MSSM:

$$\boxed{R_p = (-1)^{3(B-L)+2S}}$$

$R_p = +1$ (SM)

-1 (SUSY)

R_p conservation ⇒

Stable LSP (=Lightest SUSY Particle)

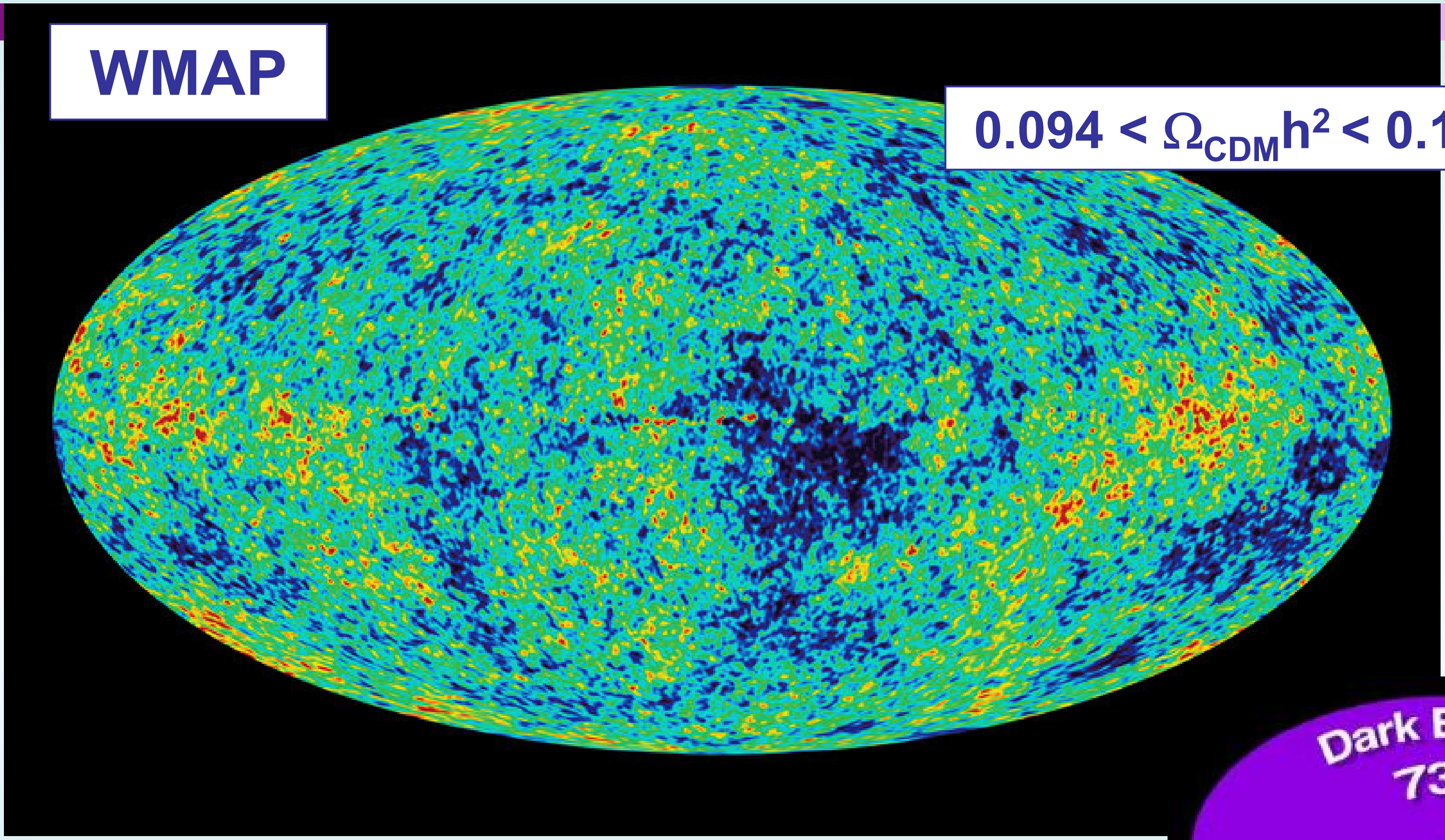
typically the lightest neutralino (good DM candidate)

Pair-production of sparticles

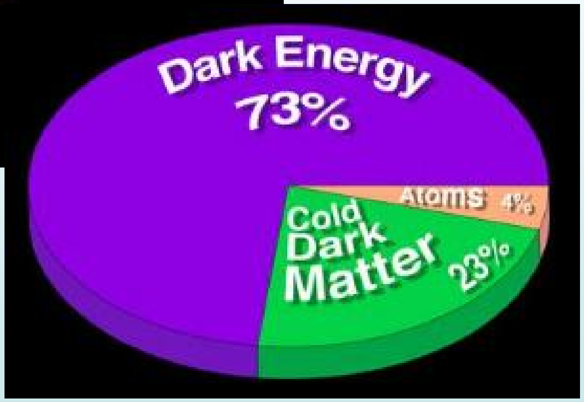
in scattering of SM particles (e.g. pp at the LHC)

In the following, will assume R-parity conservation

Neutralino as Dark Matter Constituent



$0.094 < \Omega_{CDM}h^2 < 0.136$ (95% CL)



Neutralino LSP is a good DM candidate

- stable
- electrically neutral
- weakly and gravitationally interacting

Benchmarks and Strategy

Baseline paradigm is R_p-conserving mSUGRA:

m_0	universal scalar mass
$m_{1/2}$	universal gaugino mass
A_0	trilinear soft breaking parameter at GUT scale
$\tan\beta$	ratio of Higgs vevs
$\mathrm{sgn}(\mu)$	sign of SUSY Higgs mass term

$$R_p = (-1)^{3(B-L)+2S}$$

Stable LSP
(good DM candidate)

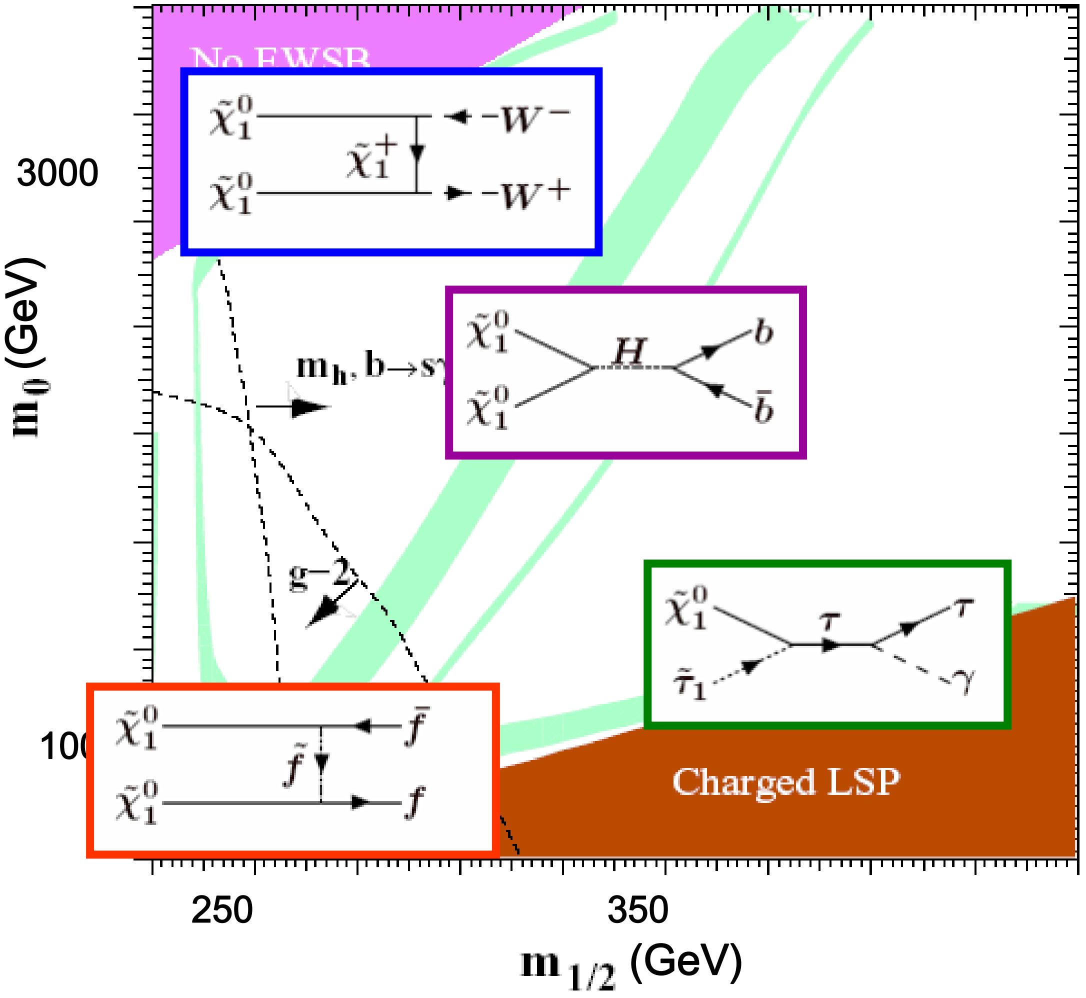
Other scenarios are also considered (GMSB, AMSB, …)

Full coverage of signatures and topologies in the entire phase space

If it's there, don't miss it !!

mSUGRA Benchmarks

Four WMAP-compatible regions, with different mechanisms for neutralino annihilation and rather different observable phenomenology



bulk

neutralino mostly bino, annihilation to ff via sfermion exchange

focus point

neutralino has strong higgsino component, annihilation to WW, ZZ

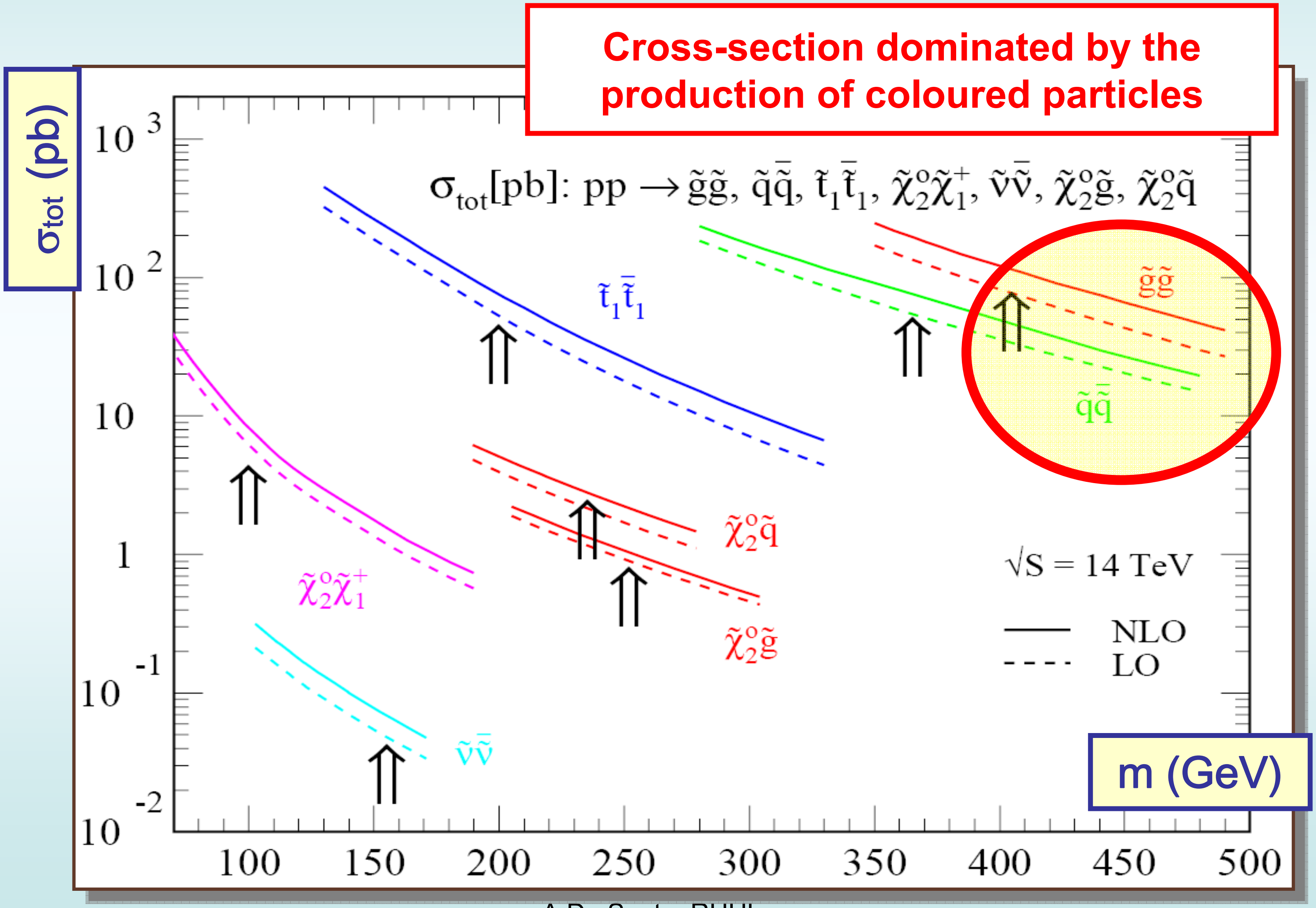
co-annihilation

pure bino, small NLSP-LSP mass difference, typically coannihilation with stau

Higgs funnel

decay to fermion pair through resonant A exchange – high tanβ

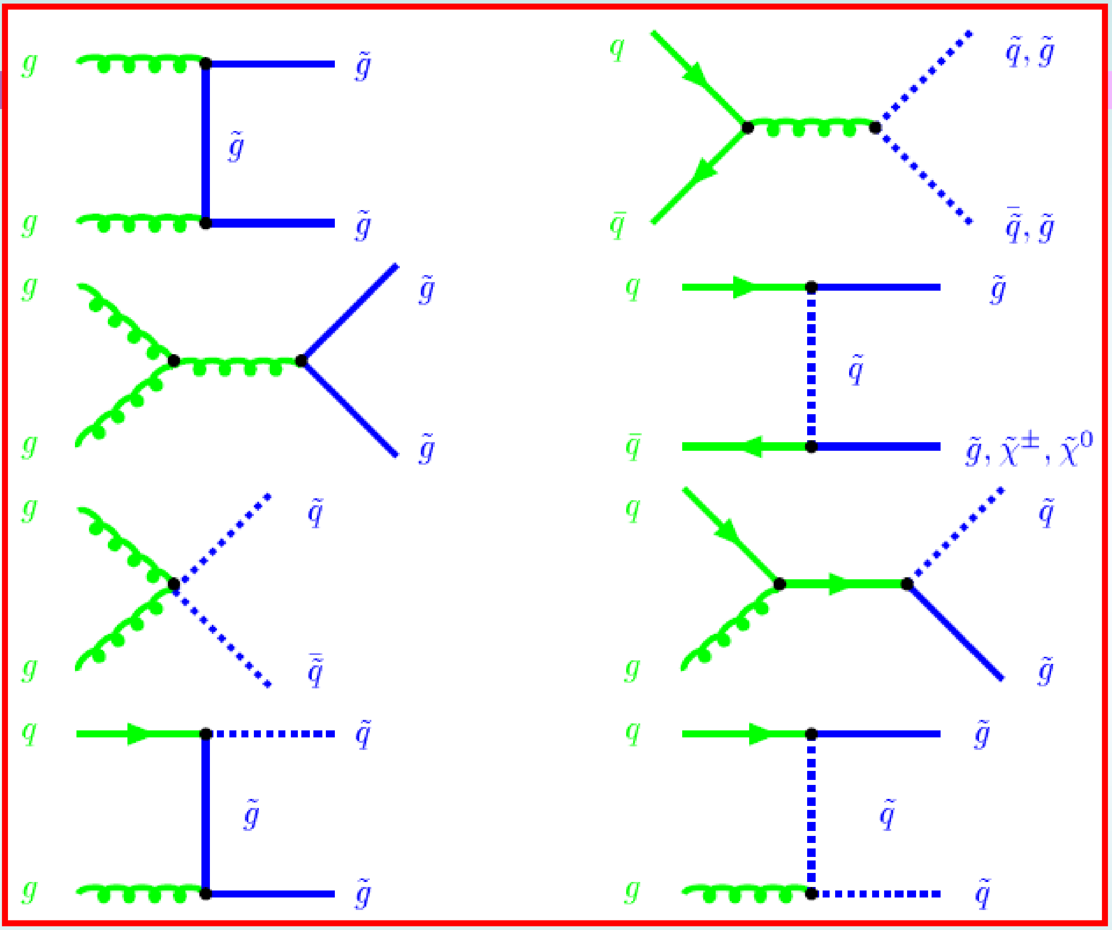
SUSY Cross-Sections

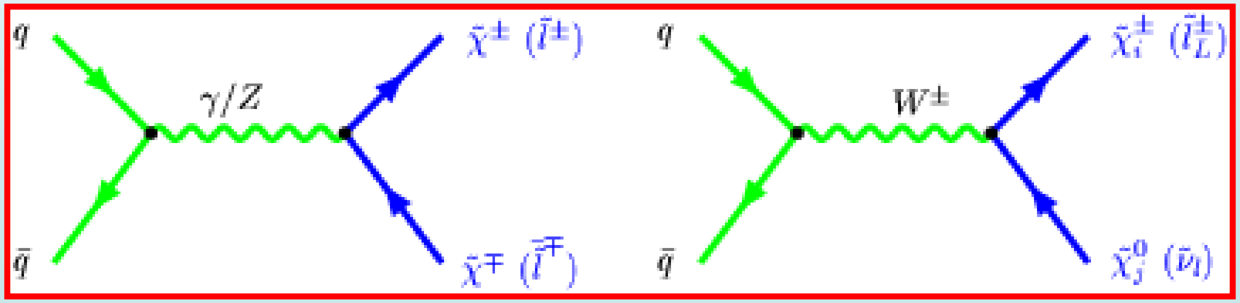


Cross-section dominated by the production of coloured particles

Production Mechanisms

Squark/Gluino Production





Direct Gaugino Production

Possible Final States

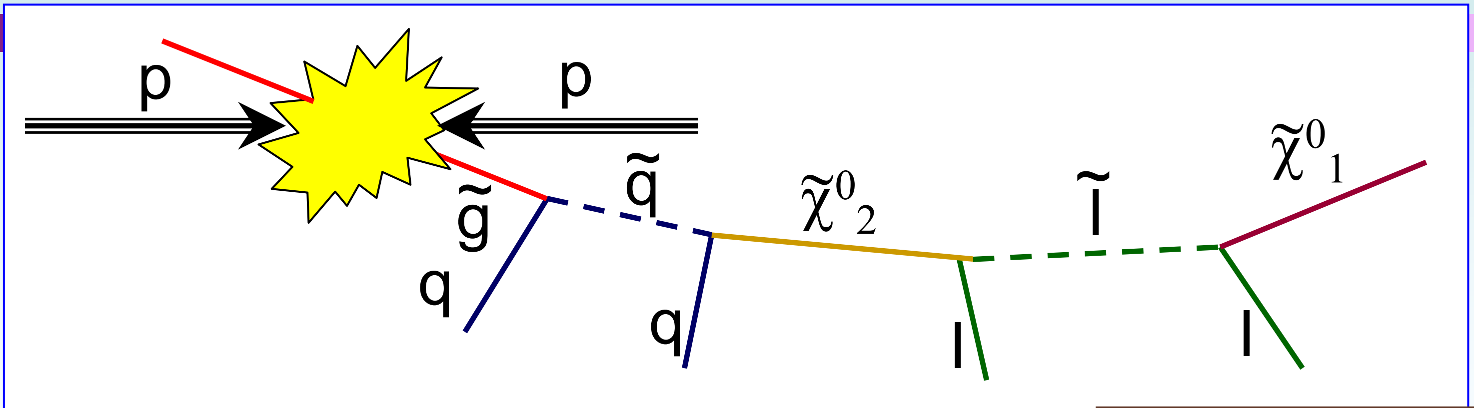
Production	Key Decay Modes		Signatures
• $\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ $q\bar{q}'\tilde{\chi}_1^\pm$ $g\tilde{\chi}_1^0$	$m_{\tilde{q}} > m_{\tilde{g}}$	$\not{E}_T$ + multijets (+leptons)
	$\tilde{q} \rightarrow q\tilde{\chi}_i^0$ $\tilde{q} \rightarrow q'\tilde{\chi}_i^\pm$	$m_{\tilde{g}} > m_{\tilde{q}}$	

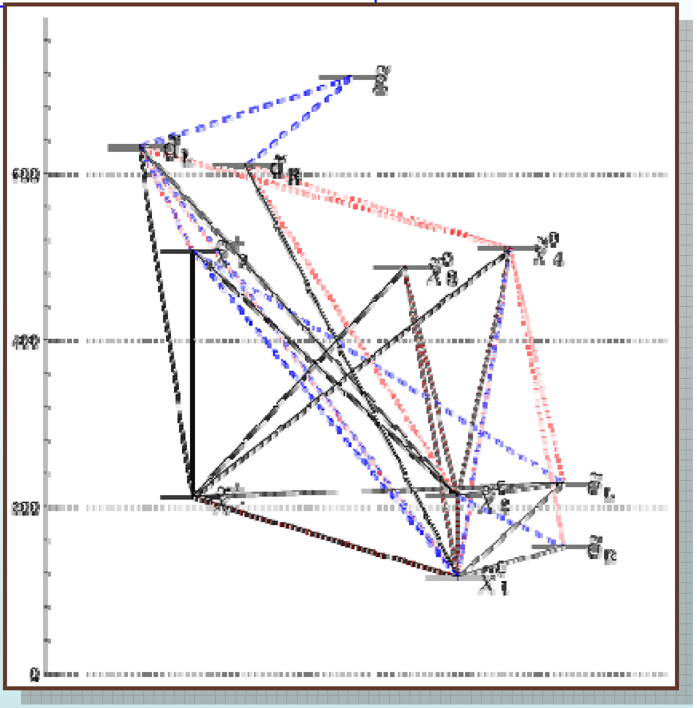
Inclusive Searches

• $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu,\ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 ll$	Trilepton $+ \not{E}_T$
	$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 ll$	Dilepton + jet $+ \not{E}_T$
• $\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \rightarrow l\tilde{\chi}_1^0 l^\pm \nu$	Dilepton $+ \not{E}_T$
• $\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 X'$	$\not{E}_T$ + Dilepton + (jets) + (leptons)
• $\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	2 acollinear jets $+ \not{E}_T$
	$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 q\bar{q}'$	single lepton $+ \not{E}_T + b's$
	$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu$	Dilepton $+ \not{E}_T + b's$
• $\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \ddot{\imath}\tilde{n}u\tilde{\nu}$	$\tilde{l}^\pm \rightarrow l \pm \tilde{\chi}_i^0, \tilde{l}^\pm \rightarrow \nu_l \tilde{\chi}_i^\pm$	Dilepton $+ \not{E}_T$
	$\tilde{\nu} \rightarrow \nu\tilde{\chi}_1^0$	Single lepton $+ \not{E}_T + (jets)$
		$\not{E}_T$

Exclusive Searches

Inclusive Searches



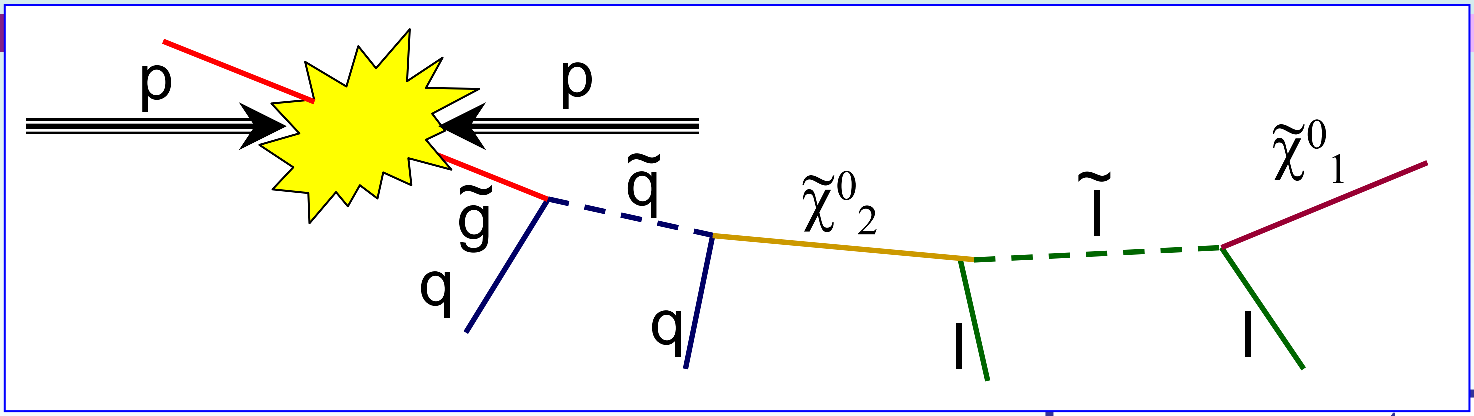


Complex long decay chains to undetected $\tilde{\chi}_1^0$

Inclusive search:

- **high multiplicity of high-p_T jets**
- **large E_T^{miss} (from escaping LSP)**
- **≥ 0 (high-pT) leptons**

Inclusive Searches



$$M_{eff} = E_T^{miss} + \sum_{jet=1}^{4} E_T^{(jet)} \left(+\, p_T(lep)\right)$$

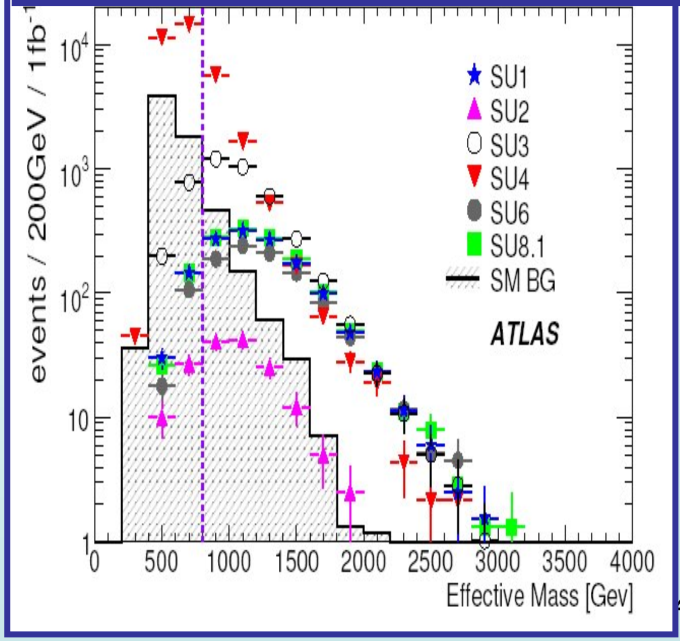
Complex long decay chains to undetected $\tilde{\chi}_1^0$

Inclusive search:

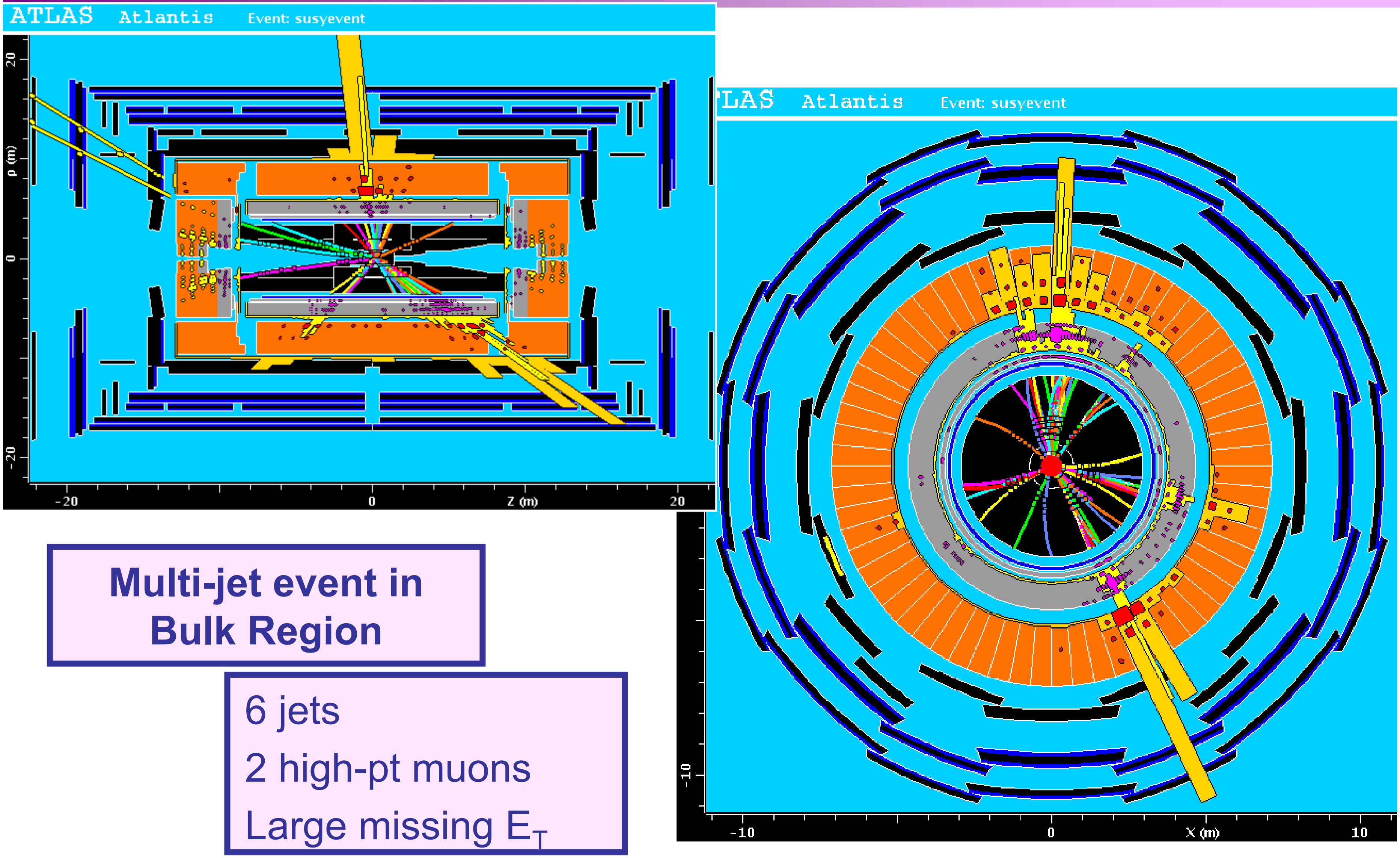
high multiplicity of high-p_T jets

large E_T^{miss} (from escaping LSP)

≥ 0 (high-pT) leptons



A (simulated!) SUSY event in ATLAS



Multi-jet event in Bulk Region

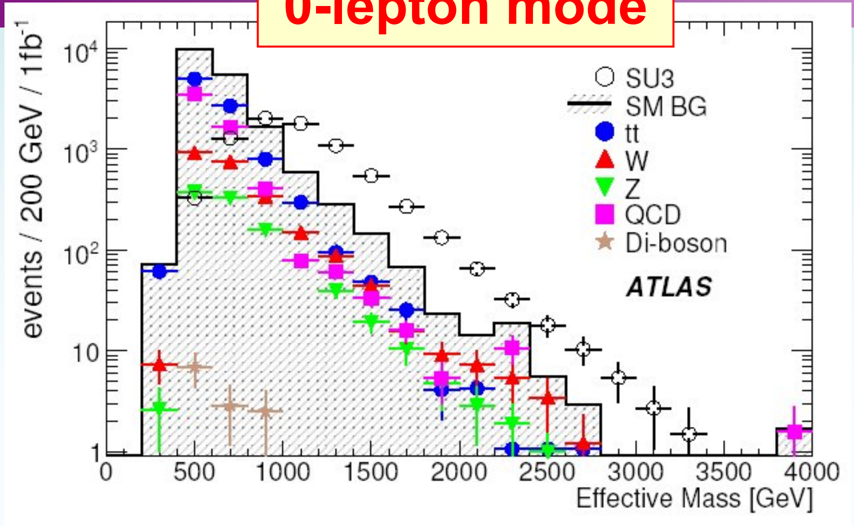
6 jets

2 high-pt muons

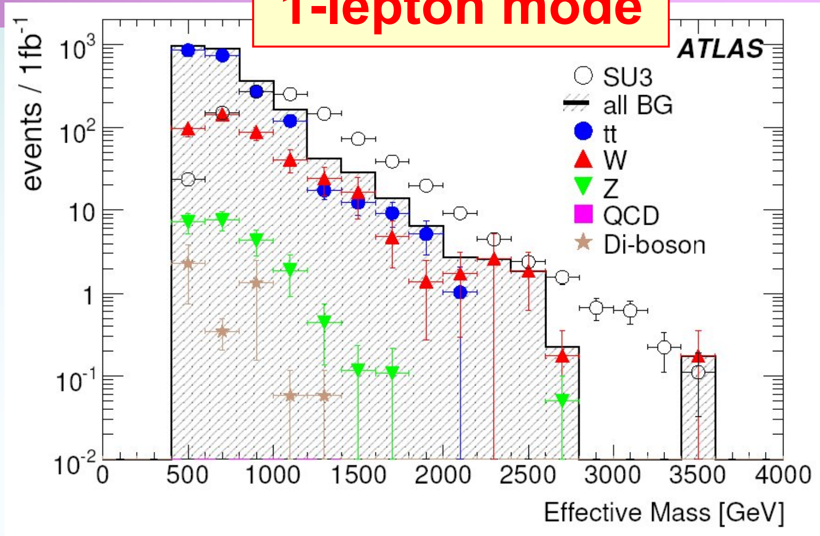
Large missing E_T

Standard Model Backgrounds

0-lepton mode



1-lepton mode



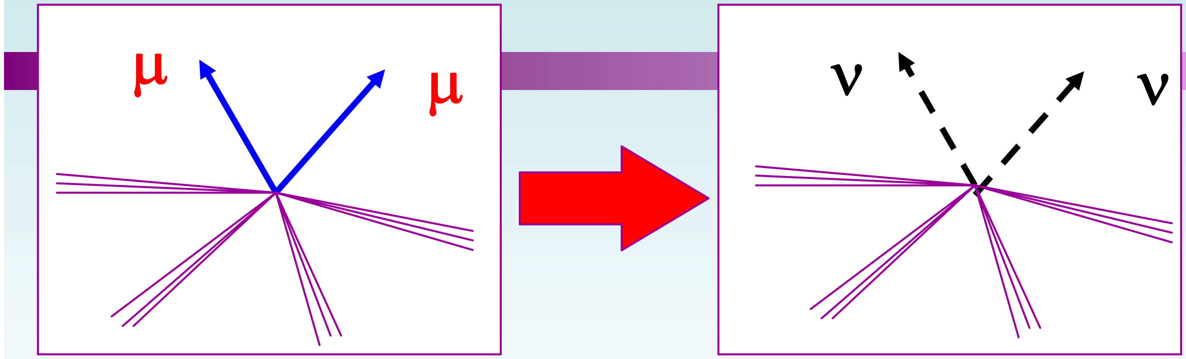
Dominant SM backgrounds:

- **multi-jet QCD**
- **W/Z+jets**
- **ttbar**
- **dibosons**

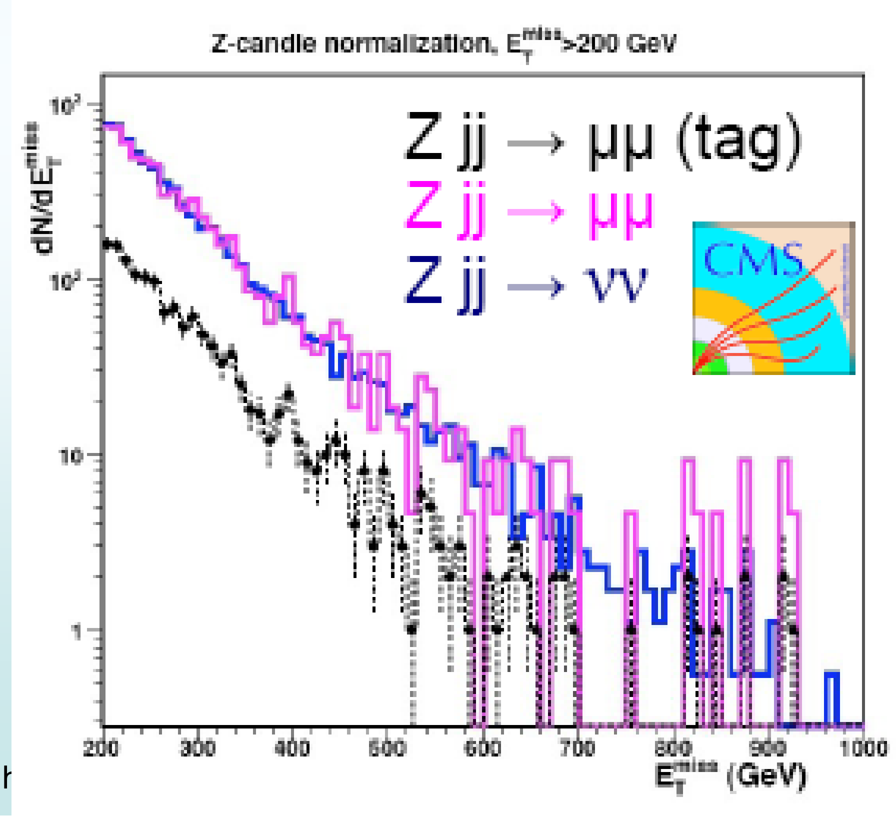
Need robust, data-driven background predictions (as well as predictions from reliable Monte Carlo simulations)

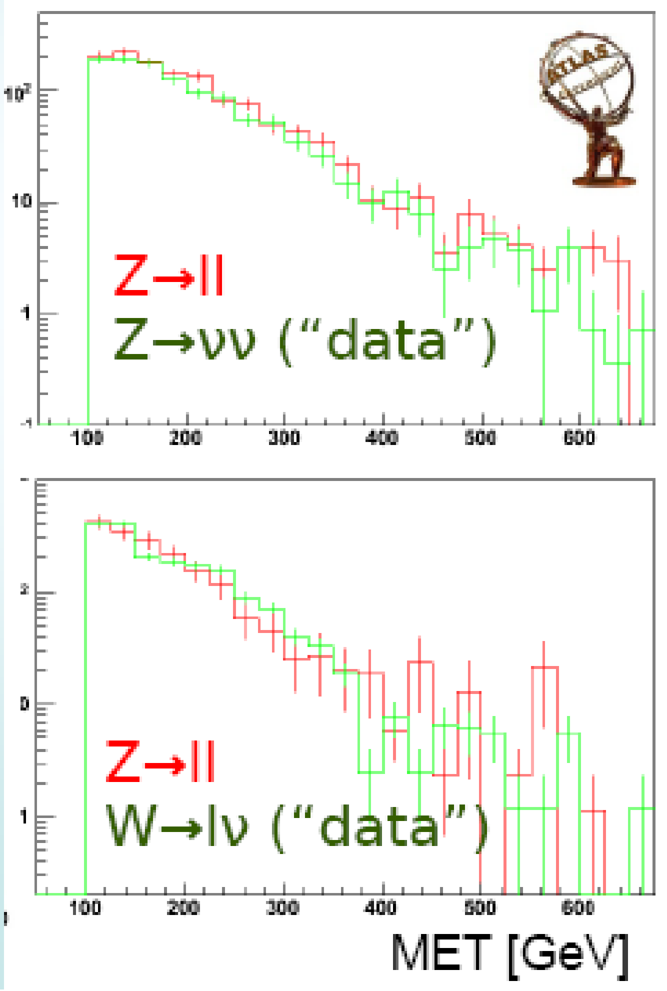
Before we can claim a discovery, we must achieve complete confidence in our understanding of the detectors, the trigger, the reconstruction and particle identification algorithms and, above all, of the SM backgrounds

Data-Driven Background Estimation – An Example

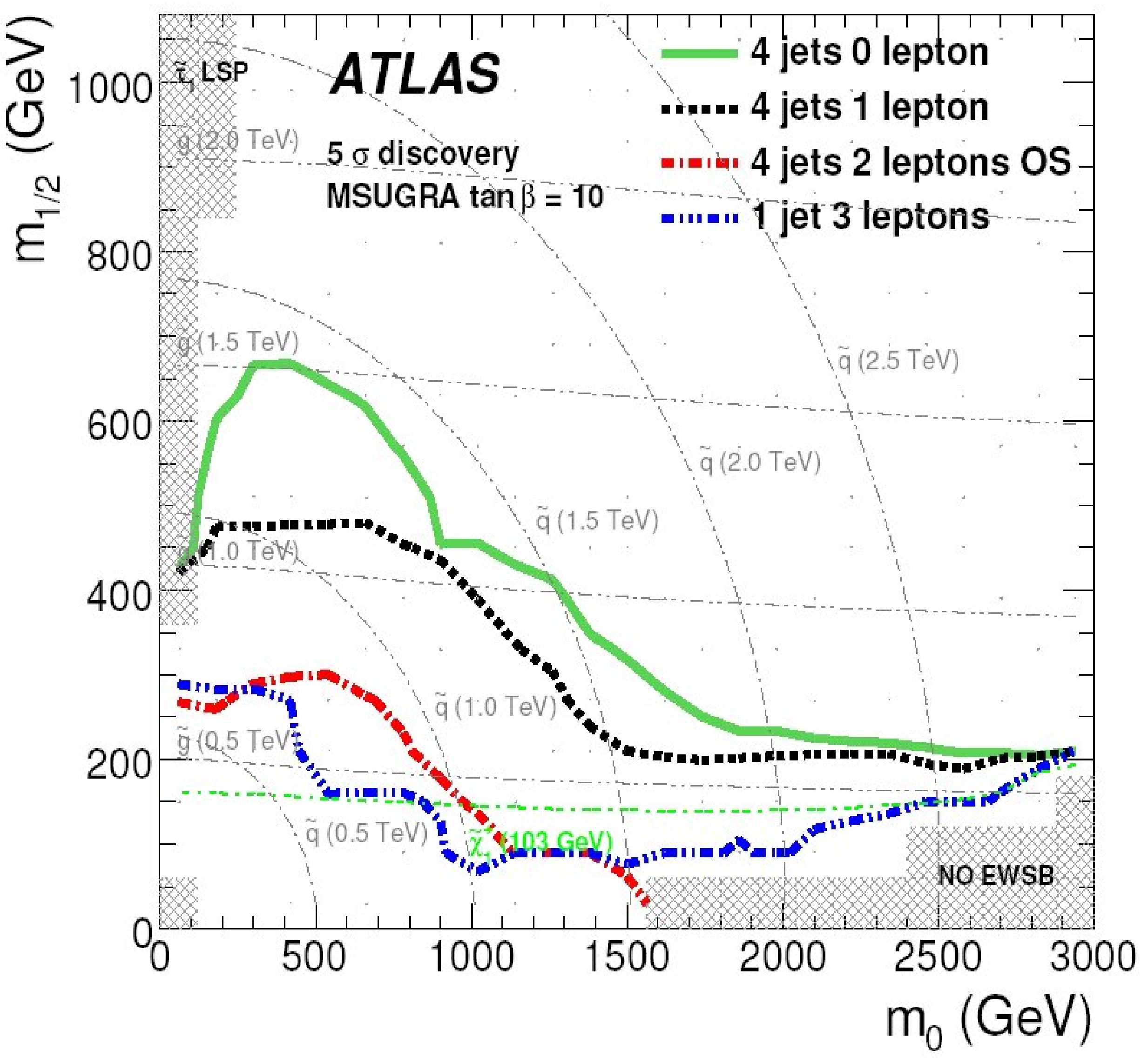


Charged lepton replacement in (Z→ll)+jets events



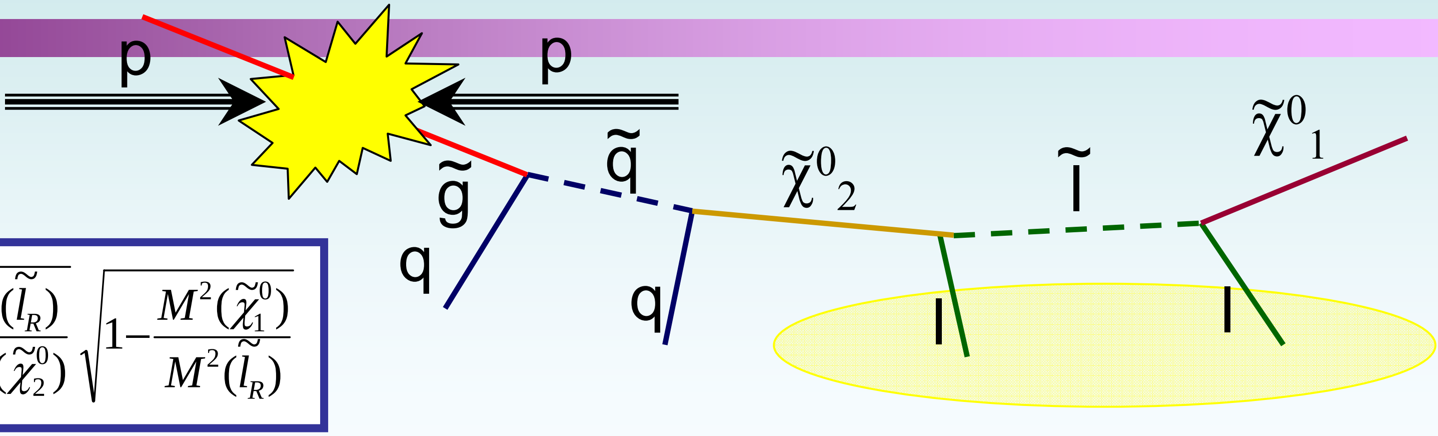


Discovery potential with 1 fb^{-1}



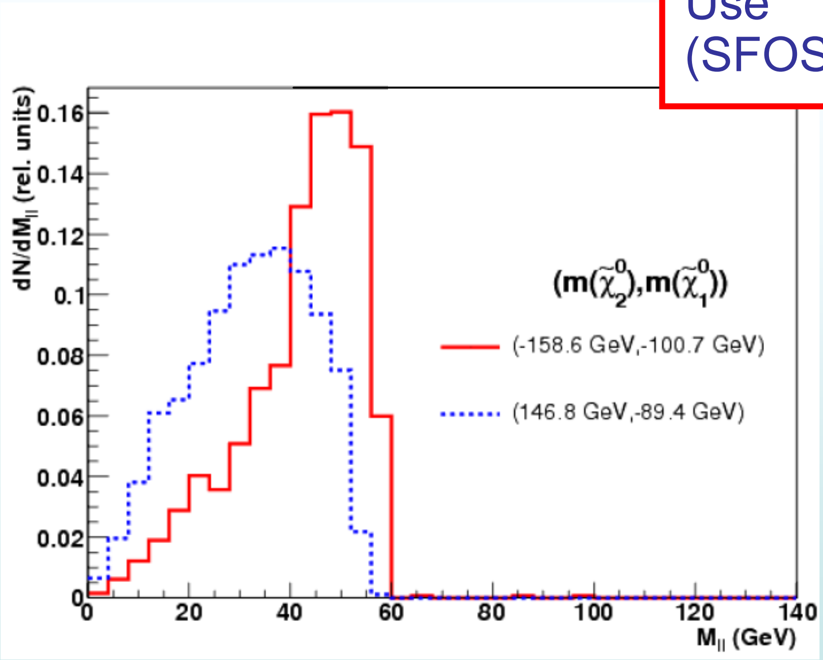
Discovery potential largely dominated by cross-sections and backgrounds

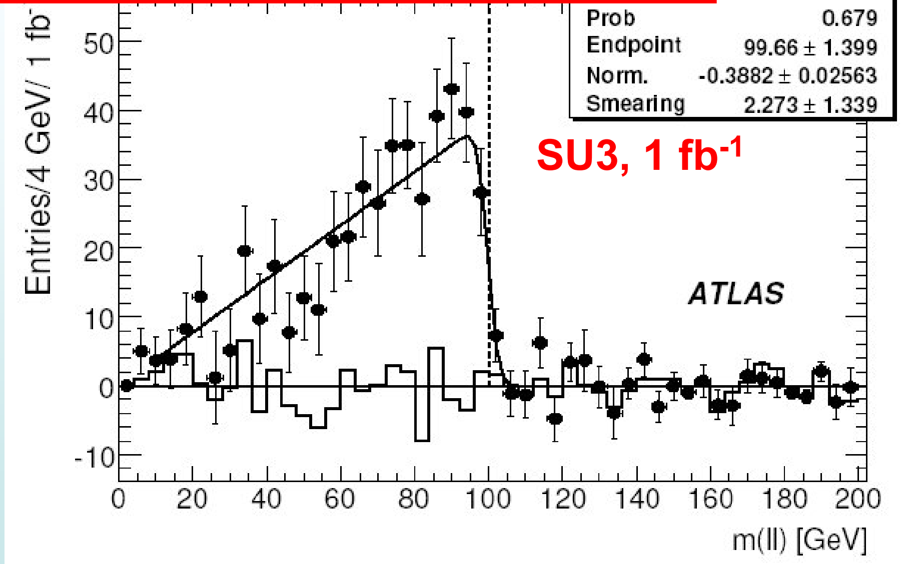
Constraining SUSY – Dilepton Edges



$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$

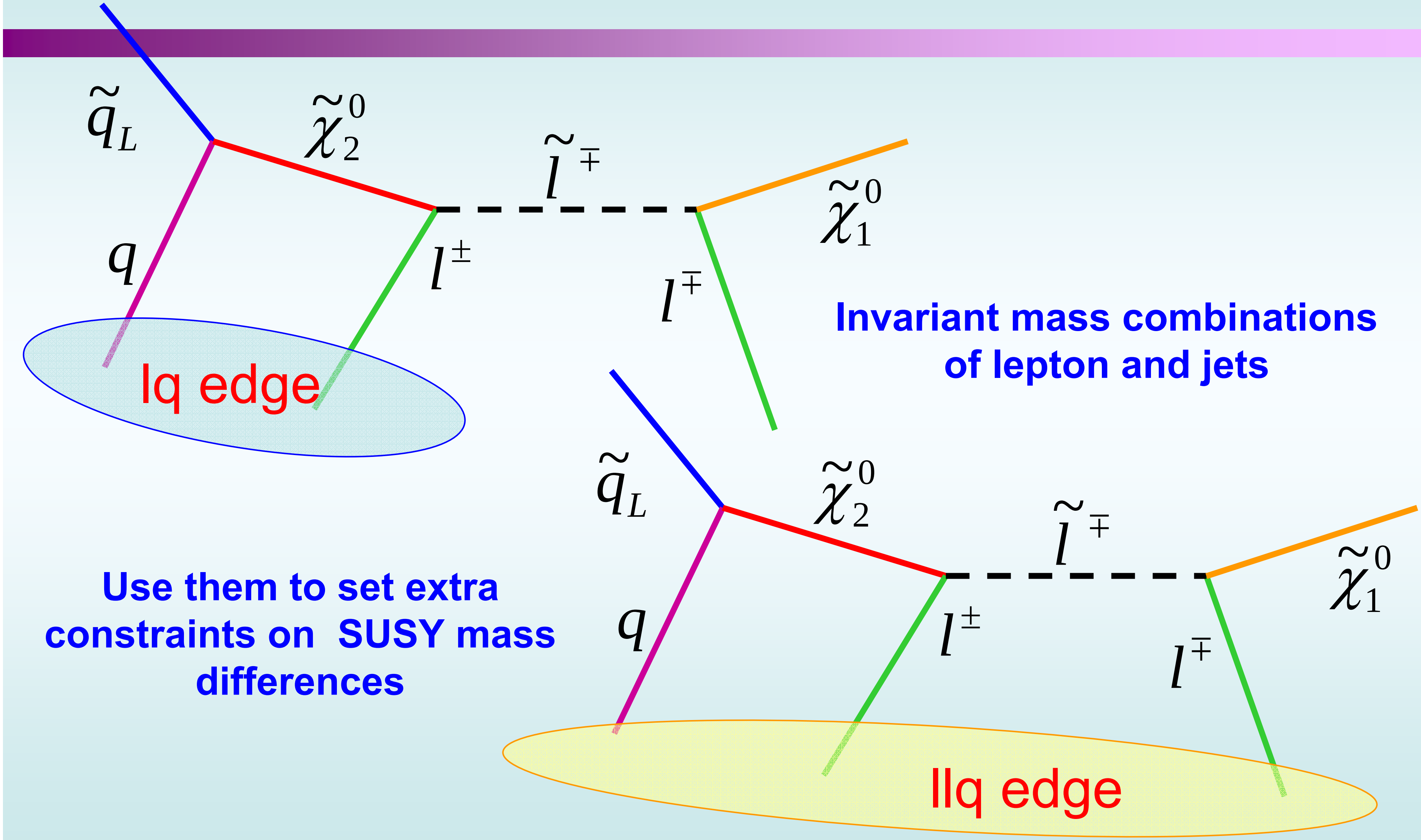
Use flavour-subtracted combination (SFOS-OFOS) to suppress backgrounds





SU3, 1 fb^{-1}

More Edges



Invariant mass combinations of lepton and jets

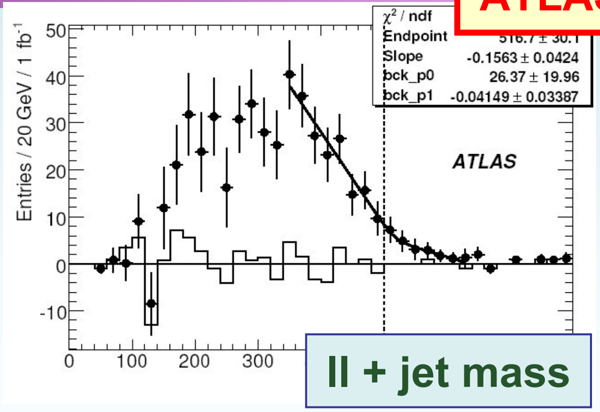
Use them to set extra constraints on SUSY mass differences

Fits to Mass Edges

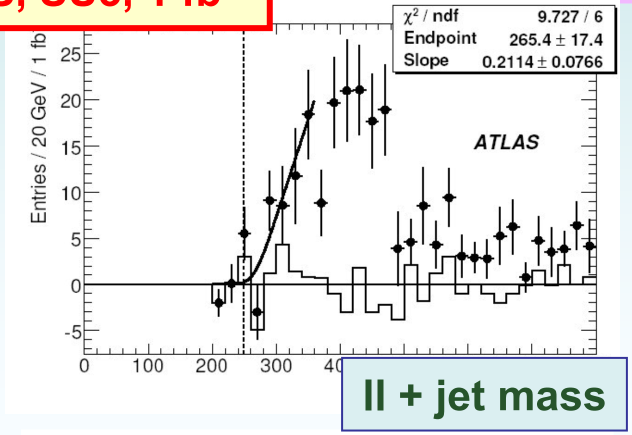
ATLAS, SU3, 1 fb^{-1}

Already with O(1 fb-1), the fits to these edges can give reasonably good estimates of SUSY mass differences, and can be used to constrain SUSY

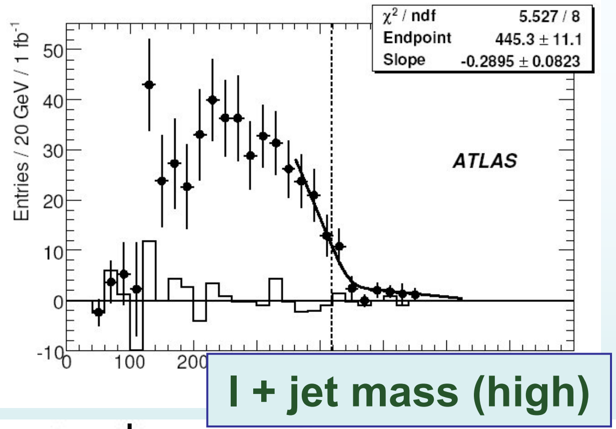
Under the assumption that the considered decay chain is the one actually realised in data



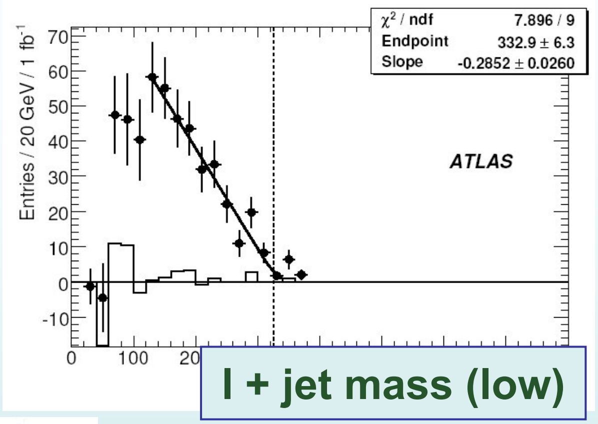
ll + jet mass



ll + jet mass



l + jet mass (high)



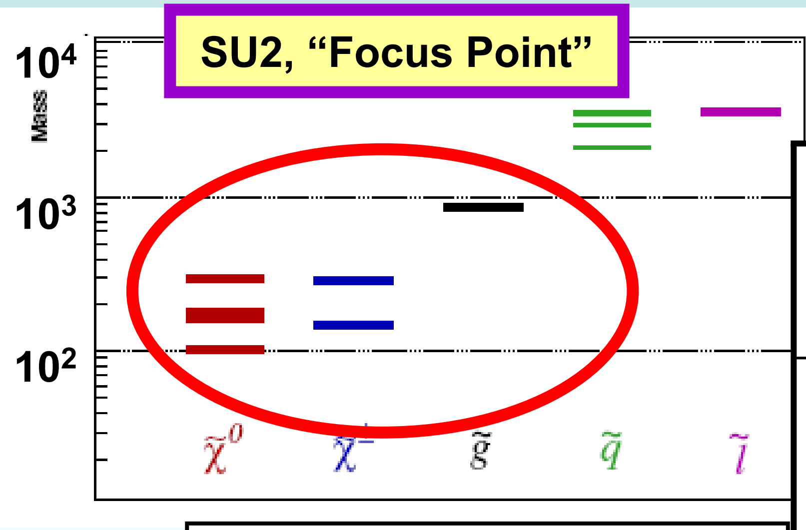
l + jet mass (low)

Endpoint	SU3 truth	SU3 measured	SU4 truth	SU4 measured
$m_{\ell\ell q}^{\max}$	501	$517 \pm 30 \pm 10 \pm 13$	340	$343 \pm 12 \pm 3 \pm 9$
$m_{\ell\ell q}^{\min}$	249	$265 \pm 17 \pm 15 \pm 7$	168	$161 \pm 36 \pm 20 \pm 4$
$m_{lq(\mathrm{low})}^{\max}$	325	$333 \pm 6 \pm 6 \pm 8$	240	$201 \pm 9 \pm 3 \pm 5$
$m_{lq(\mathrm{high})}^{\max}$	418	$445 \pm 11 \pm 11 \pm 11$	340	$320 \pm 8 \pm 3 \pm 8$

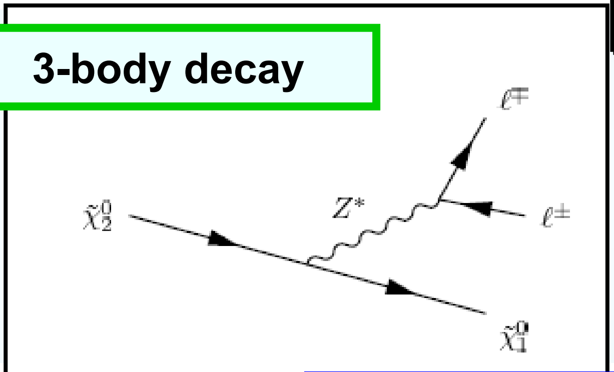
Trileptons in ATLAS

Point	mSUGRA Parameters					Cross Sections (pb)	
	m_0	$m_{1/2}$	A_0	$\tan\beta$	$\mathrm{sgn}(\mu)$	Tot.	3-lep
SU2	**3550**	**300**	**0**	**10**	**+**	**7.2**	**0.07**
SU3	**100**	**300**	**-300**	**6**	**+**	**27.7**	**0.30**
SU4	**200**	**160**	**-400**	**10**	**+**	**402.2**	**2.5**

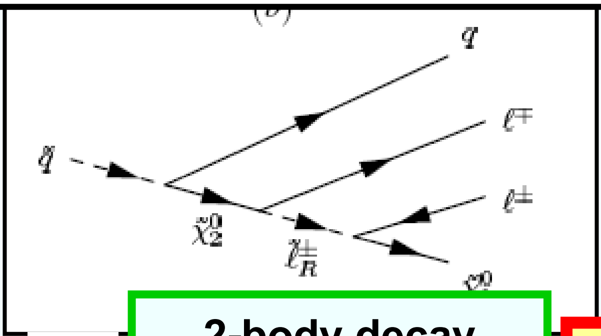
SU2, “Focus Point”



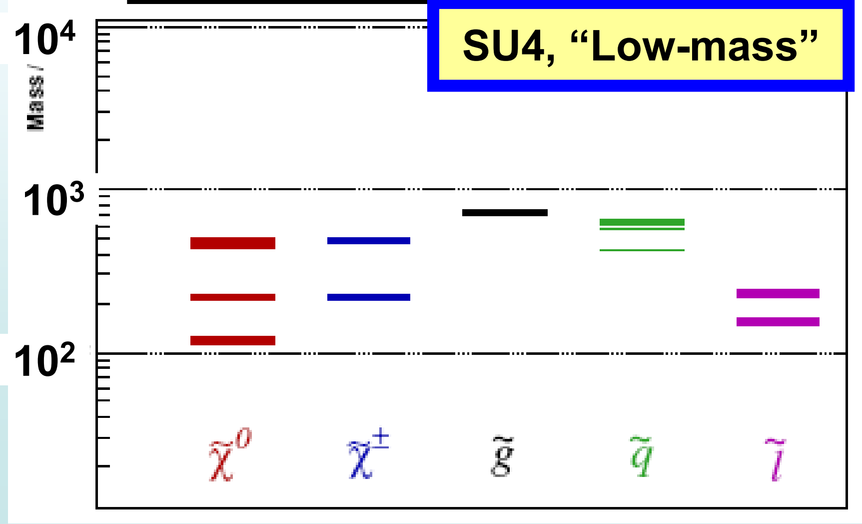
3-body decay



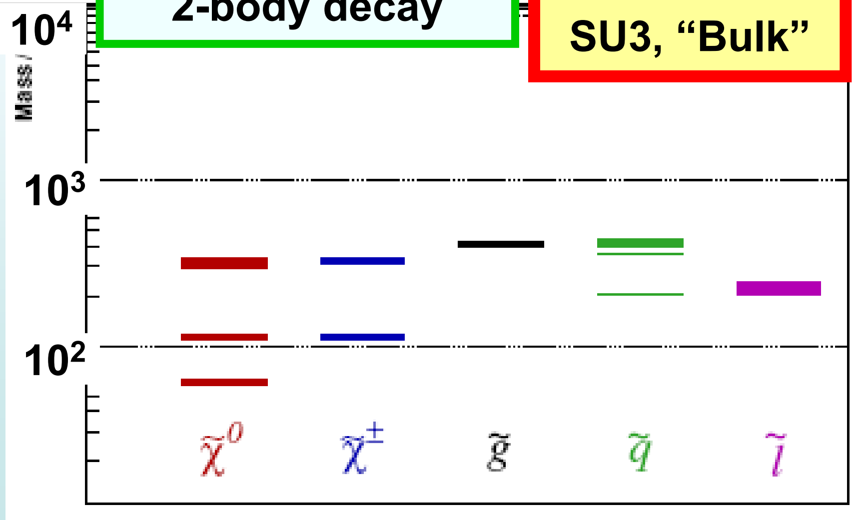
2-body decay



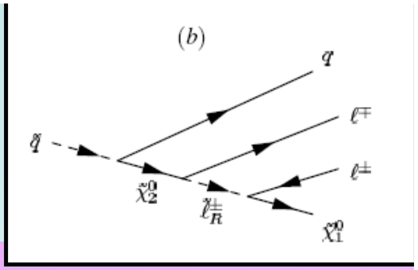
SU4, “Low-mass”



SU3, “Bulk”



Inclusive Trilepton Analysis – I



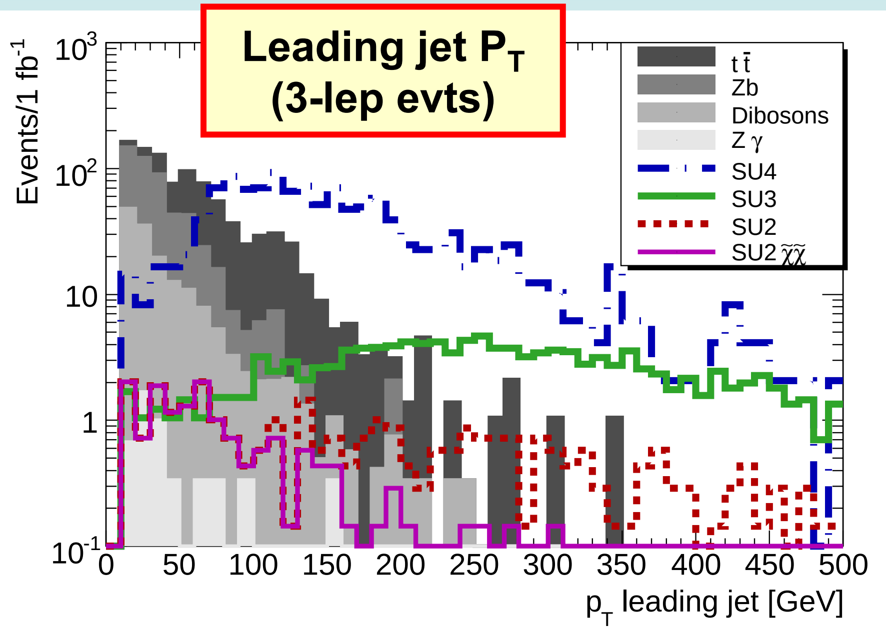
Crucially simple analysis flow:

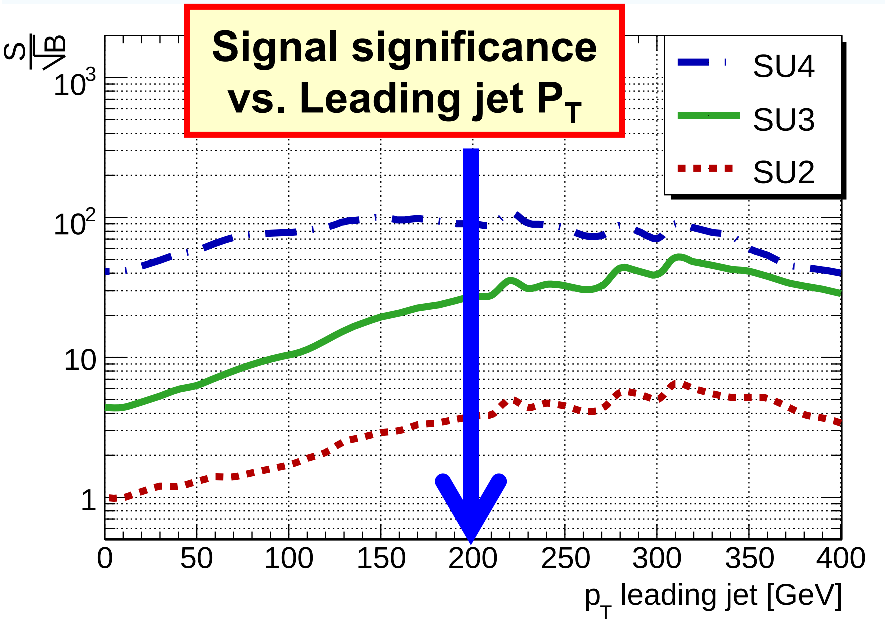
- 3 isolated leptons (e, μ)

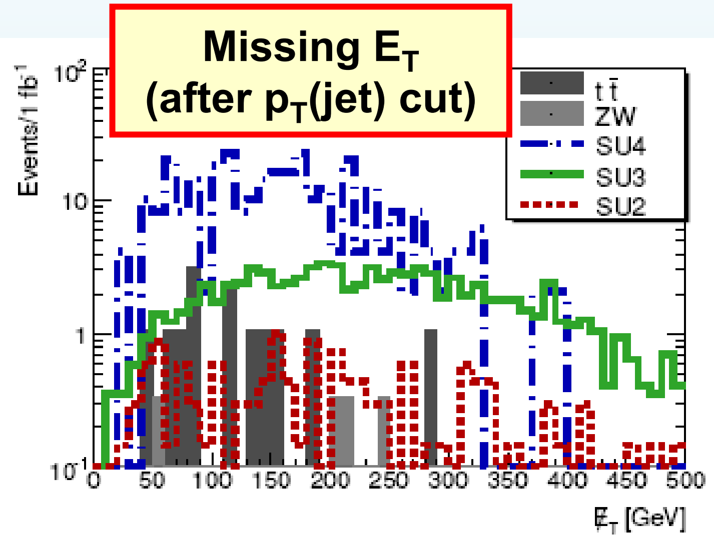
  (taus are next step!)

- At least 1 high-pt jet

Don't need large missing E_T cut – good !!


Leading jet P_T (3-lep evts)


Signal significance vs. Leading jet P_T


Missing E_T (after p_T(jet) cut)

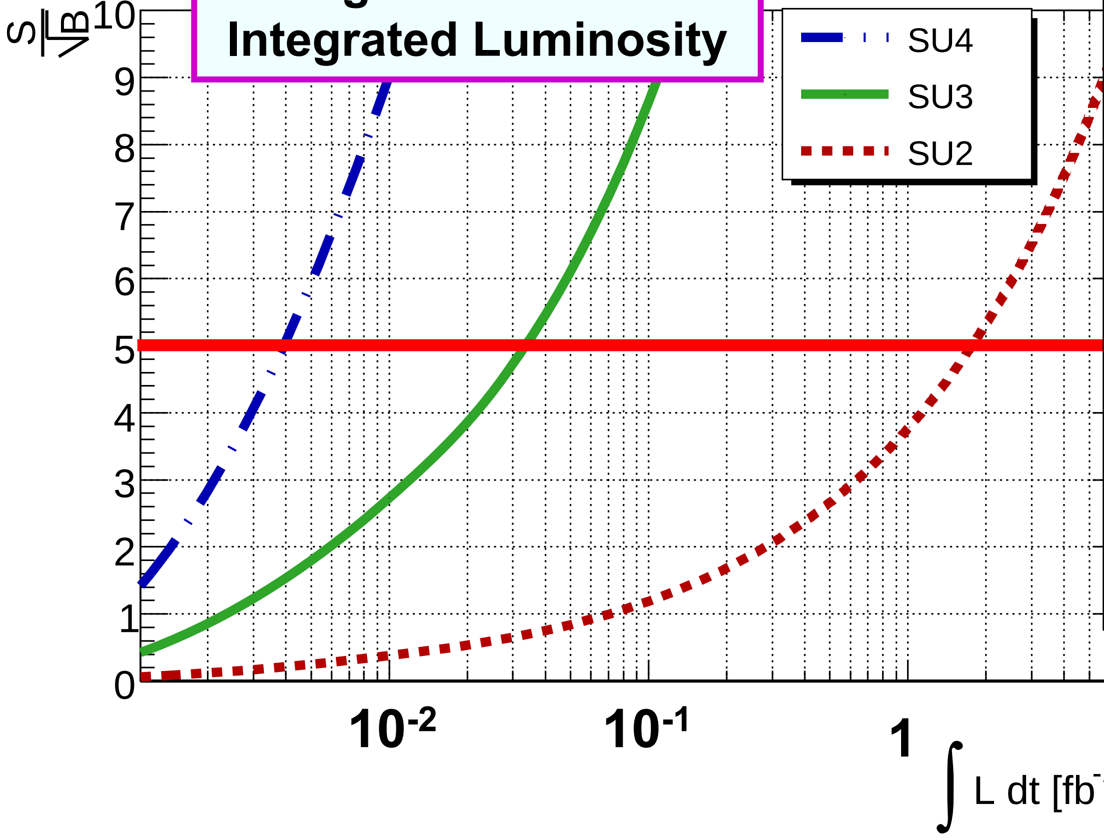
Inclusive Trilepton Analysis

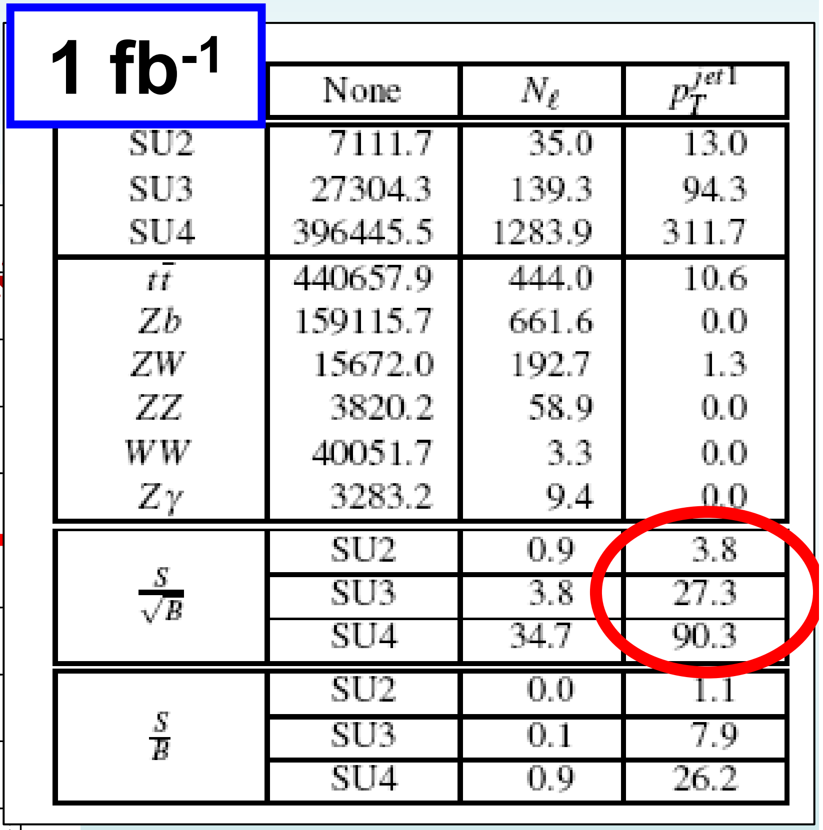
A .De Santo et al., Trilepton signatures at ATLAS, ATL-PHYS-INT-2008-037

A. De Santo et al., Expected performance of the ATLAS experiment, CERN-OPEN-2008-020

Potentially an early SUSY discovery channel!!

Significance vs. Integrated Luminosity

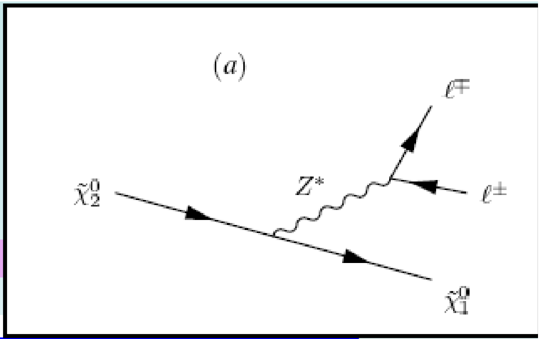


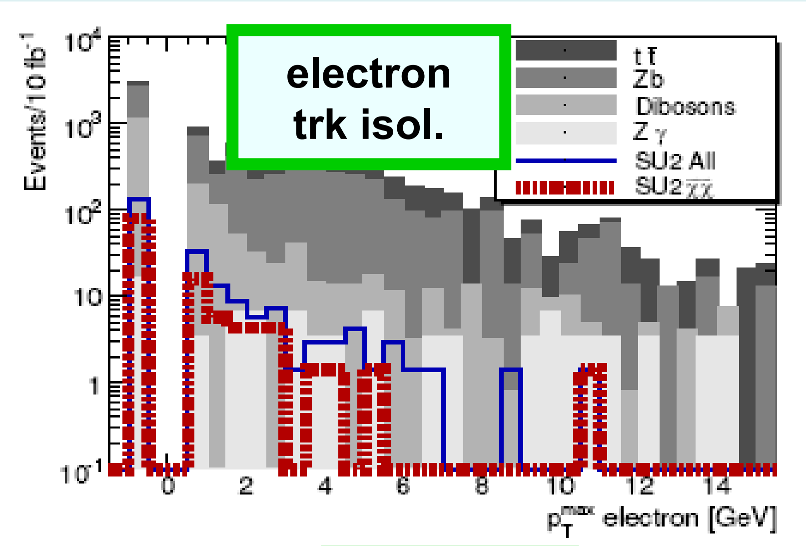


1 fb^{-1}

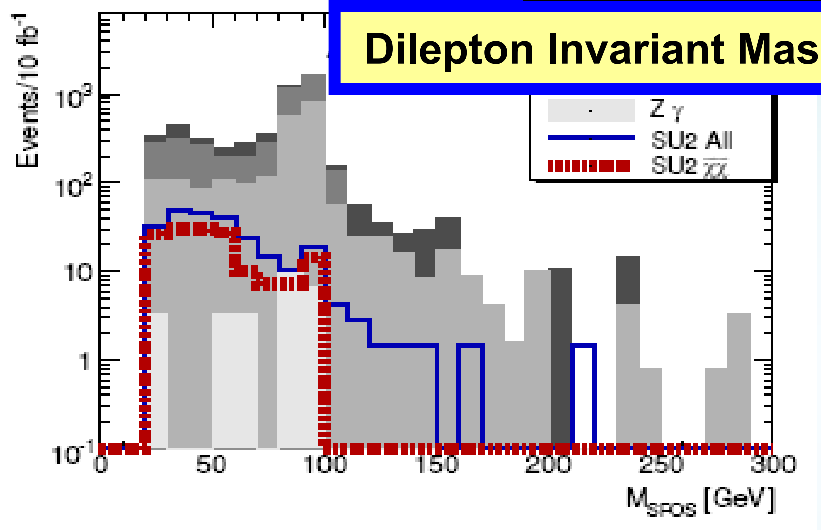
	None	N_ℓ	p_T^{jet1}
SU2	7111.7	35.0	13.0
SU3	27304.3	139.3	94.3
SU4	396445.5	1283.9	311.7
$t\bar{t}$	440657.9	444.0	10.6
Zb	159115.7	661.6	0.0
ZW	15672.0	192.7	1.3
ZZ	3820.2	58.9	0.0
WW	40051.7	3.3	0.0
$Z\gamma$	3283.2	9.4	0.0
$\frac{S}{\sqrt{B}}$	SU2	0.9	3.8
	SU3	3.8	27.3
	SU4	34.7	90.3
$\frac{S}{B}$	SU2	0.0	1.1
	SU3	0.1	7.9
	SU4	0.9	26.2

Exclusive 3-lep Analysis at Focus Point

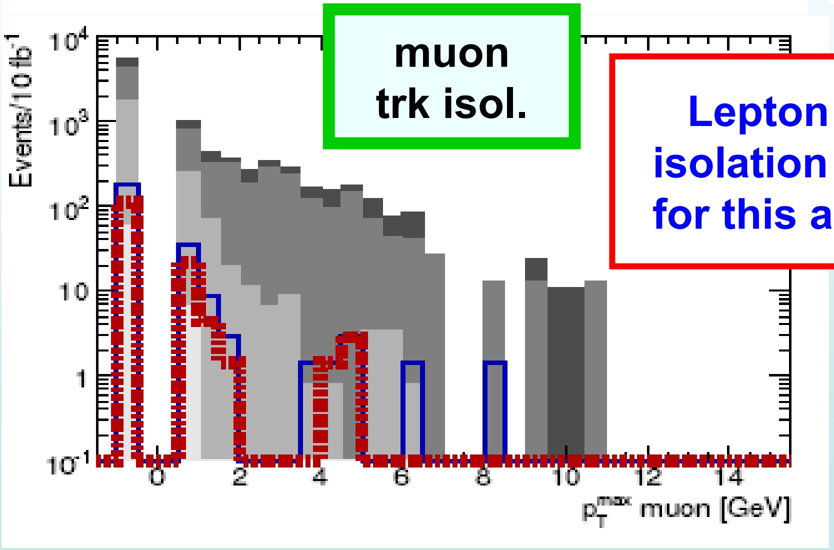




electron trk isol.

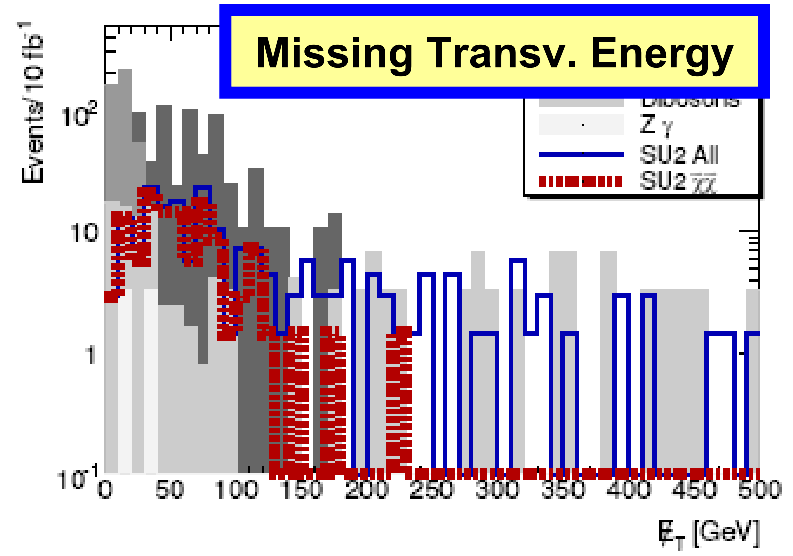


Dilepton Invariant Mass



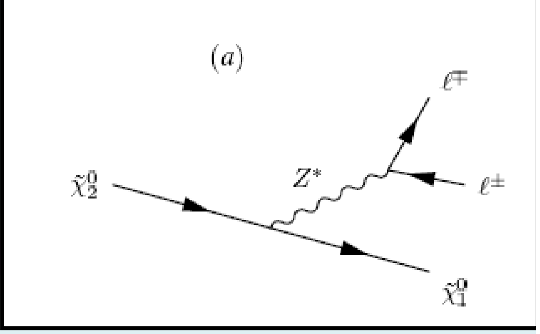
muon trk isol.

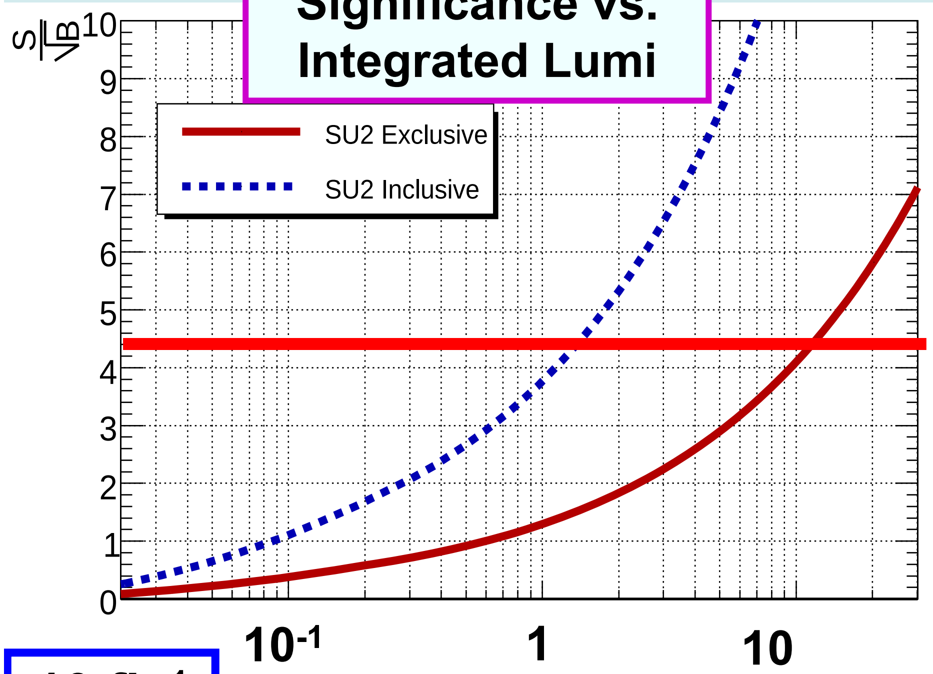
Lepton track isolation crucial for this analysis



Missing Transv. Energy

Exclusive 3-lep Analysis at Focus Point



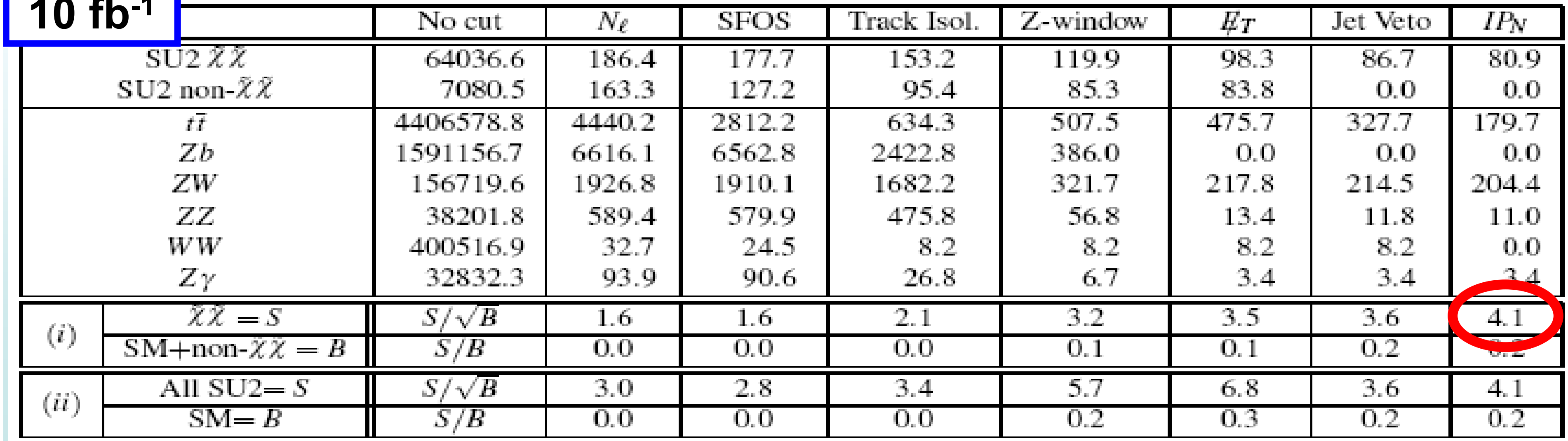

Significance vs. Integrated Lumi

Not an early physics channel

But potentially the only way to see SUSY if both scalars and gluino are too heavy!

A. De Santo et al., ditto

10 fb^{-1}



		No cut	N_ℓ	SFOS	Track Isol.	Z-window	$\not{E}_T$	Jet Veto	IP_N
	SU2 $\tilde{\chi}\tilde{\chi}$	64036.6	186.4	177.7	153.2	119.9	98.3	86.7	80.9
	SU2 non-$\tilde{\chi}\tilde{\chi}$	7080.5	163.3	127.2	95.4	85.3	83.8	0.0	0.0
	$t\bar{t}$	4406578.8	4440.2	2812.2	634.3	507.5	475.7	327.7	179.7
	Zb	1591156.7	6616.1	6562.8	2422.8	386.0	0.0	0.0	0.0
	ZW	156719.6	1926.8	1910.1	1682.2	321.7	217.8	214.5	204.4
	ZZ	38201.8	589.4	579.9	475.8	56.8	13.4	11.8	11.0
	WW	400516.9	32.7	24.5	8.2	8.2	8.2	8.2	0.0
	$Z\gamma$	32832.3	93.9	90.6	26.8	6.7	3.4	3.4	3.4
(i)	$\tilde{\chi}\tilde{\chi} = S$	$S/\sqrt{B}$	1.6	1.6	2.1	3.2	3.5	3.6	4.1
	SM+non-$\tilde{\chi}\tilde{\chi} = B$	S/B	0.0	0.0	0.0	0.1	0.1	0.2	0.2
(ii)	All SU2$= S$	$S/\sqrt{B}$	3.0	2.8	3.4	5.7	6.8	3.6	4.1
	SM$= B$	S/B	0.0	0.0	0.0	0.2	0.3	0.2	0.2

CONCLUSIONS

Conclusions

With the LHC turn on, new physics at the TeV scale is becoming accessible experimentally for the first time at an accelerator

SUSY provides a well motivated extension to the Standard Model

Very excitingly, we might have the possibility to observe "dark matter in a laboratory"

LET THE SHOW BEGIN !!